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The potential of thermal groundwater use in urban environments

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Be Water, My Friend.
Bruce Lee

Summary

A solution to reducing the current consumption of fossil fuels, particularly in the field of building heating and cooling, lies in the increased use of shallow geothermal energy. However, due to the existing intensive use of the subsurface in urban areas, conflicts of use are increasingly foreseeable. Therefore, a sensible use of underground resources requires a quantitative estimation of the technologically achievable energy potentials using scientifically based tools, in order to ensure a sustainable and conflict-free expansion of shallow geothermal energy. The present cumulative dissertation addresses this very challenge of developing a method for comprehensive potential estimation for thermal groundwater use in urban environments, taking into account relevant legal and technical constraints. In order to make these open scientific questions and possible solutions accessible to a wide professional audience, the results were presented in three publications that were published in internationally recognized journals in the research field.

Initially, shallow geothermal energy, and in particular the thermal use of groundwater, was rarely taken into account in energy plans or municipal energy strategies. The main reason for neglecting thermal groundwater use was the lack of suitable methods for quantitative potential estimation, which would allow comparison with heating or cooling demands. The first publication now closes this gap by presenting a method for quantitative evaluation of the potential for thermal use of groundwater and its integration into spatial energy planning. The method can be adapted to local legal and operational limits in order to sensibly limit pump rates and, based on this, estimate the thermal output that can be achieved by a well doublet. The constraints for technically limiting pump rates are as follows: *i*) a threshold for groundwater drawdown in the extraction well, *ii*) a limit for the groundwater rise in the injection well, and *iii*) a threshold for avoiding a hydraulic breakthrough between the two wells. For additional spatial evaluation, the hydraulic influence of neighbouring well doublets with the maximum pump rates before hydraulic breakthrough is simulated. Thus, the TAP (Thermal Aquifer Potential) method combines mathematical relationships derived from non-linear regression analysis using results from numerical parameter studies.

An application of the TAP method is demonstrated with the potential assessment in Munich. The evaluation revealed that in most areas outside the city's district heating system, a pump rate of over $1 L/s$ can be sustainably provided, and thus groundwater heat pumps or groundwater-supplied district heating networks can make a significant contribution to the city's renewable heat supply. As the potential assessment is also evaluated at the property level, the results were able to flow directly into the city of Munich's energy use plan for the first time and also form an elementary basis for the city's energy strategy in the subsequent municipal heat planning. In addition, the results are compared with measurement data from existing systems, which show that conservative forecasts of peak extractions are met.

After the introduction of the TAP method for classic two-well systems, an integration of the method's results into results from related methods that evaluate more theoretical potentials on larger scales was previously lacking. The aim of the second publication is therefore to link related methods at the city level and to bridge the gap between theoretical and technical potentials. The study presents an application-oriented management approach that combines different methods of potential analysis. With the help of numerical 3D groundwater flow and heat transport models, the dynamics at the city and district level are simulated. Based on this, the technically feasible extraction rates of well doublets for groundwater heat pump systems are quantified using the 2D box models of the TAP method. Using the case study of Basel (Switzerland), areas with high advective heat flow and high heat transport were initially identified, for which large theoretical energy potentials can be derived. On a more detailed scale, it was shown that for individual city districts, the technical potentials for an 'active' thermal use with two-well systems can reach outputs of up to 1.2MW. For 'passive' installations of thermally activated building components that integrate into the groundwater, the energy potentials are 4 to 40Wm^{-2}. The results can be integrated into urban energy plans and support architects, city planners, and potential users in obtaining initial site-specific information about the technical feasibility of shallow geothermal energy systems.

Since the TAP method assesses the legally and technically constraint potential of thermal groundwater use, the economic aspect has so far not been taken into account in the potential evaluation. Besides the required temperature levels on the demand side, the efficiency of thermal groundwater use primarily depends on the groundwater temperature. Particularly in urban areas, groundwater temperature can be highly dynamic in time and space due to anthropogenic influences. A reliable estimation of heat pump performance based on heat source temperatures was previously not possible, as the groundwater temperatures at the time of heat pump operation were often not known. To close this knowledge gap, the third publication presents a detailed investigation of the thermal conditions of the Quaternary groundwater aquifer in Munich. Shallow aquifers beneath cities are highly influenced by anthropogenic heat sources, which leads to the formation of extensive subsurface urban heat islands. In addition to anthropogenic factors, natural factors also influence the subsurface temperature. However, due to the high temporal dynamics in the urban environment, the impact of individual factors is difficult to capture. Especially for shallow aquifers, seasonal temperature fluctuations often overlay the influence of existing heat sources or sinks.

For the city of Munich, the dominant anthropogenic and natural influences on groundwater temperature are identified, and it is analysed how the influences change with increasing depth in the subsurface. For this purpose, depth temperature profiles from 752 selected groundwater monitoring wells are used. Since the measurements were carried out at different times, a statistical approach was developed to compensate for the different seasonal temperature influences using a "passive heat tracing" method. In addition, a score is proposed to spatially assess the thermal stress on the aquifer. A multiple regression analysis with four natural and nine anthropogenic factors identified surface sealing as the strongest, and the district heating network as a weak, but significant, warming influence on the groundwater temperature. The natural factors, aquifer thickness, depth-to-water, and Darcy velocity, show a significant cooling influence on the groundwater temperature. Moreover, it is shown that local influencing factors such as thermal groundwater uses, surface waters, and underground structures do not make a significant contribution to the citywide temperature distribution in Munich. The subsequent depth-dependent analysis revealed that the influence of aquifer thickness and depth-to-water increases with depth, while the influence of Darcy's velocity decreases and the influence of surface sealing and the district heating network remains relatively constant. In summary, the study shows that the most critical factor in reducing future warming of groundwater in cities is to avoid further sealing of the soil, restore permeability of heavily sealed areas, and preserve open landscapes.

In conclusion, it can be stated that the developed methods and conducted investigations provide an appropriate basis for integrating the thermal use of groundwater into municipal heat planning and energy strategies. The results of the potential assessment have been successfully included in the energy plan of the heating and cooling sector of the City of Munich and serve as a basis to draft actions towards a renewable heating and cooling supply. In addition, the results were published on the city's web portal for geodata, making them accessible to the general public. The TAP method has already been anchored in the Bavarian guidelines for energy planning as a recommended procedure for calculating technical potentials. The guideline aims to standardize energy planning and is currently the central instrument for municipalities in awarding energy plans. Finally, the TAP method is already being used across Bavaria to provide the quantitative potentials of thermal groundwater use in further suitable regions as part of a follow-up project. The application of the method at the state level underlines the relevance of the conducted research. Therefore, it can be concluded that the main goal, namely the quantitative integration of thermal groundwater use into the energy planning of Munich and, in the long term, at the state level, has been successfully achieved.

Zusammenfassung

Eine Lösung zur Reduzierung des aktuellen Verbrauchs an fossilen Brennstoffen, insbesondere im Bereich der Gebäudeheizung und -kühlung, besteht in der verstärkten Nutzung der oberflächennahen Geothermie. Allerdings sind aufgrund der bestehenden intensiven Nutzung des Untergrunds in urbanen Gebieten vermehrt Nutzungskonflikte absehbar. Eine sinnvolle Nutzung der unterirdischen Ressourcen erfordert daher eine quantitative Abschätzung der technologisch erreichbaren Energiepotenziale mithilfe wissenschaftlich fundierter Instrumente, um einen nachhaltigen und konfliktfreien Ausbau der oberflächennahen Geothermie sicherzustellen. Die vorliegende kumulative Dissertation stellt sich genau dieser Herausforderung, eine Methode zur umfassenden Potenzialabschätzung für die thermische Grundwassernutzung im urbanen Umfeld unter Berücksichtigung relevanter rechtlicher und technischer Rahmenbedingungen zu entwickeln. Um diese offenen wissenschaftlichen Fragestellungen und mögliche Lösungen einem breiten Fachpublikum zugänglich zu machen, wurden die Ergebnisse in drei Publikationen präsentiert, die in international anerkannten Zeitschriften des Forschungsfelds veröffentlicht wurden.

Zunächst wurde die oberflächennahe Geothermie und insbesondere die thermische Nutzung des Grundwassers nur selten in Energieplänen oder kommunalen Energiestrategien berücksichtigt. Der Hauptgrund für die Vernachlässigung der thermischen Grundwassernutzung war das Fehlen von geeignete Methoden zur quantitativen Potenzialabschätzung, welche einen Abgleich mit dem Wärme- oder Kältebedarf ermöglichen würden. Die erste Veröffentlichung schließt nun diese Lücke, indem eine Methode zur quantitativen Bewertung des Potenzials für die thermische Nutzung des Grundwassers und dessen Integration in die räumliche Energieplanung vorgestellt wird. Die Methode kann an lokale gesetzliche und betriebsrelevante Grenzen angepasst werden, um Pumpraten sinnvoll zu begrenzen und darauf aufbauend die thermische Leistung abzuschätzten, die von einer Brunnendoublette erreicht werden kann. Die Randbedingungen für die technische Beschränkung von Pumpraten sind wie folgt: *i*) ein Schwellenwert für die Absenkung im Entnahmebrunnen, *ii*) ein Grenzwert für den Grundwasseranstieg im Injektionsbrunnen und *iii*) ein Schwellenwert zur Vermeidung eines hydraulischen Kurzschlusses zwischen den beiden Brunnen. Für die räumliche Bewertung wird die hydraulische Beeinflussung benachbarter Brunnendoubletten mit den maximalen Pumpraten vor dem hydraulischen Kurzschluss simuliert. Die TAP-Methode (Thermal Aquifer Potential) kombiniert mathematische Beziehungen, die durch nichtlineare Regressionsanalyse abgeleitet wurden, mit Ergebnissen aus numerischen Parameterstudien. Eine Demonstration der TAP-Methode wird anhand der Potenzialabschätzung für München gegeben. Eine durchge-

führte Bewertung ergab, dass in den meisten Bereichen außerhalb des Fernwärmegebiets der Stadt eine Pumprate von über $1L/s$ nachhaltig geliefert werden kann und somit dezentrale Grundwasserwärmepumpen oder grundwasserversorgte Nahwärmenetze einen signifikanten Beitrag zur regenerativen Wärmeversorgung der Stadt leisten können. Da die Potenzialermittlung auch auf Grundstücksebene ausgewertet wird, konnten die Ergebnisse erstmals direkt in den Energienutzungsplan der Stadt München einfließen und stellen auch in der weiterführenden kommunalen Wärmeplanung eine elementare Grundlage der städtischen Wärmestrategie dar. Darüber hinaus werden die Ergebnisse mit Messdaten bestehender Anlagen verglichen, die belegen, dass konservative Prognosen der Spitzenentnahme erreicht werden.

Nach der Vorstellung der TAP-Methode für klassische Zwei-Brunnen-Systeme fehlte bisher eine klare Abgrenzung der Methode gegenüber verwandten Methoden, die eher theoretische Potenziale auf größeren Maßstäben bewerten. Das Ziel der zweiten Veröffentlichung ist daher die Verknüpfung verwandter Methoden auf Stadtebene und das Schlagen einer Brücke zwischen theoretischen und technischen Potenzialen. Die Studie stellt einen anwendungsorientierten Managementansatz vor, der verschiedene Methoden der Potenzialanalyse kombiniert. Mit Hilfe von numerischen 3D-Grundwasserströmungs- und Wärmetransportmodellen wird die Dynamik auf Stadt- und Quartiersebene erfasst. Darauf basierend werden mit den 2D-Boxmodellen der TAP-Methode die technisch realisierbaren Entnahmeraten von Brunnendoubletten für Grundwasserwärmepumpensysteme quantifiziert. Am Beispiel von Basel (Schweiz) konnten zunächst Gebiete mit hohem advektiven Wärmestrom und hohem Wärmetransport identifiziert werden, für die sich große theoretische Energiepotenziale ableiten lassen. Auf einer detaillierteren Skala wurde gezeigt, dass für einzelne Stadtquartiere die technischen Potenziale für eine "aktive" thermische Nutzung mit Zwei-Brunnen-Systemen Leistungen von bis zu $1{,}2MW$ erreichen können. Bei "passiven" Installationen von thermisch aktivierten Bauteilen, die ins Grundwasser einbinden, liegen die Energiepotenziale bei 4 bis $40Wm^{-2}$. Die Ergebnisse können in städtische Energiepläne integriert werden und unterstützen Architekten, Stadtplaner und potenzielle Nutzer dabei, erste standortspezifische Informationen über die technische Machbarkeit von oberflächennahen geothermischen Entzugssystemen zu erhalten.

Da die TAP-Methode das rechtlich und technisch begrenzte Potenzial der thermischen Grundwassernutzung bewertet, wurde der wirtschaftliche Aspekt in der Potenzialbewertung bisher nicht berücksichtigt. Neben den erforderlichen Temperaturniveaus auf der Nachfrageseite hängt die Effizienz der thermischen Grundwassernutzung vor allem von der Grundwassertemperatur ab. Insbesondere in städtischen Gebieten kann die Grundwassertemperatur durch anthropogene Einflüsse zeitlich und räumlich sehr dynamisch sein. Eine verlässliche Abschätzung der Leistung von Wärmepumpen basierend auf den Temperaturen der Wärmequelle war bisher nicht möglich, da die Grundwassertemperaturen zum Zeitpunkt des Wärmepumpenbetriebs oft nicht bekannt waren. Um diese Wissenslücke zu schließen, wird in der dritten Veröffentlichung eine detaillierte Untersuchung der thermischen Verhältnisse des quartären Grundwasserleiters in München präsentiert. Oberflächennahe Grundwasserleiter in Städten werden in hohem Maße durch anthropogene Wärmequellen beeinflusst, was zur Bildung ausgedehnter unterirdischer städtischer Wärmeinseln führt. Neben den anthropogenen Faktoren beeinflussen auch natürliche Faktoren die Temperatur im Untergrund. Die Wirkung der einzelnen Faktoren ist jedoch aufgrund der hohen zeitlichen Dynamik im städtischen Umfeld schwer zu erfassen. Insbesondere bei oberflächennahen Grundwasserleitern überlagern saisonale Temperaturschwankungen oft den Einfluss vorhandener Wärmequellen oder -senken.

Für die Stadt München identifizieren wir die dominierenden anthropogenen und natürlichen Einflüsse auf die Grundwassertemperatur und analysieren, wie sich diese Einflüsse mit zunehmender Tiefe im Untergrund verändern. Dazu werden Tiefentemperaturprofile von 752 ausgewählten Grundwassermessstellen genutzt. Da die Messungen zu unterschiedlichen Zeitpunkten erfolgten, wurde ein statistischer Ansatz entwickelt, um die unterschiedlichen jahreszeitlichen Temperatureinflüsse mithilfe einer "passive heat tracing" Methode auszugleichen. Zusätzlich wird ein Indikator zur räumlichen Bewertung der thermischen Belastung des Grundwasserleiters vorgeschlagen. Eine multiple Regressionsanalyse mit vier natürlichen und neun anthropogenen Faktoren identifiziert die Oberflächenversiegelung als den stärksten und das Fernwärmenetz als einen schwachen, aber signifikanten erwärmenden Einfluss auf die Grundwassertemperatur. Die natürlichen Faktoren, Grundwassermächtigkeit, Flurabstand und Darcy-Geschwindigkeit, zeigen einen signifikanten kühlenden Einfluss auf die Grundwassertemperatur. Des Weiteren wird gezeigt, dass lokale Einflussfaktoren wie thermische Grundwassernutzungen, Oberflächengewässer und unterirdische Strukturen keinen wesentlichen Beitrag zur stadtweiten Temperaturverteilung in München leisten. Die anschließende tiefenabhängige Analyse ergab, dass der Einfluss der Grundwassermächtigkeit und des Flurabstands mit der Tiefe zunimmt, während der Einfluss der Darcy-Geschwindigkeit abnimmt und der Einfluss der Oberflächenversiegelung und des Fernwärmenetzes relativ konstant bleibt. Zusammenfassend zeigt die Studie, dass der kritischste Faktor für die Verringerung einer zukünftigen Erwärmung des Grundwassers in Städten darin besteht, die weitere Versiegelung des Bodens zu vermeiden, die Durchlässigkeit stark versiegelter Flächen wiederherzustellen und offene Landschaften zu erhalten.

Zusammenfassend lässt sich festhalten, dass die entwickelten Methoden und durchgeführten Untersuchungen eine geeignete Grundlage für die Integration der thermischen Grundwassernutzung in die kommunale Wärmeplanung und in Energiestrategien bilden. Die Ergebnisse der Potenzialbewertung wurden erfolgreich in den Energienutzungsplan des Wärme- und

Kältesektors der Stadt München aufgenommen und dienen als Grundlage für die Entwicklung von Maßnahmen zur Erreichung einer nachhaltigen Wärme- und Kälteversorgung. Darüber hinaus wurden die Ergebnisse auf dem Webportal für Geodaten veröffentlicht, um sie einer breiten Öffentlich-keit zugänglich zu machen. Auch wurde die TAP-Methode bereits im Bayerischen Leitfaden für Energienutzungsplanung als empfohlene Vorgehensweise zur Berechnung des technischen Potenzials verankert. Der Leitfaden strebt eine Standardisierung der Energienutzungsplanung an und ist derzeit das zentrale Instrument für Kommunen bei der Vergabe von Energienutzungsplänen. Schließlich wird die TAP-Methode bereits bayernweit angewandt, um im Rahmen eines Folgeprojektes die quantitativen Potenziale der thermischen Grundwassernutzung in weiteren geeigneten Regionen zu liefern. Die Anwendung der Methode auf Landesebene unterstreicht die Relevanz der durchgeführten Forschung. Somit kann festgestellt werden, dass das Hauptziel, nämlich die quantitative Integration der thermischen Grundwassernutzung in die Energieplanung von München und langfristig auf Landesebene, erfolgreich erreicht wurde.

Declaration of authorship

I, Fabian Böttcher, declare that the thesis entitled *"The potential of thermal groundwater use in an urban environment"* and the work presented in this thesis are both my own, and have been generated by me as a result of my own original research. I confirm that:

- where I have quoted from the work of others, the source is always given
- where any parts of this thesis have been previously submitted for a degree at the Technical University of Munich or any other institution, this has been clearly stated
- I have acknowledged all main sources of help
- all published own work (authorship) or co-authored published work, regarding paper and conference proceedings originating of this thesis, are given in the following.

In compliance with Appendix 6, Article 6(2) of the Regulations for the Award of Doctoral Degrees (effective January 1^{st}, 2014), a one-page summary of each full research paper, highlighting the candidate's individual contributions to each, is included below. For concise reading an author contribution statement is given, as well. For detailed information about the CRediT (Contributor Roles Taxonomy) authorship statement, please refer to doi: 10.1002/leap.1210.

Accepted publications (ISI-listed, full research paper, peer-reviewed):

TAP – Thermal Aquifer Potential:
A quantitative method to assess the spatial potential for the thermal use of groundwater
Fabian Böttcher, Alessandro Casasso, Gregor Götzl & Kai Zosseder
Renewable Energy
doi: 10.1016/j.renene.2019.04.086

CRediT authorship contribution statement: Fabian Böttcher: Conceptualisation, Methodology, Formal analysis, Data Curation, Validation, Writing, Visualisation; Alessandro Casasso: Conceptualisation, Review & Editing, Funding acquisition; Gregor Götzl: Conceptualisation, Review & Editing, Supervision; Kai Zosseder: Conceptualisation, Funding acquisition, Review & Editing, Supervision, Project administration, Funding acquisition.

Author Contribution: All main steps of the research were conducted independently by me. A summarising abstract of the work is given in Chapter 4. In the course of this study, I played the leading role across all integral domains, each contributing to the successful realization of our objectives. Initially, I drafted the study's concept and defined its scope and trajectory. Methodologically, I independently developed comprehensive framework that underpinned the analytical approach. This involved crafting methodologies in steady scientific exchange with my co-authors and subsequently writing the code that executed all simulations of the numerical parameter study. In addition, I performed the formal analyses on the acquired simulation results, leading to the fitting of three regression functions that form the bedrock of the developed TAP-method.

A crucial step was also the curation of the simulated datasets. With attention to detail, non-convergent results had to be identified and excluded in the extensive dataset, ensuring the reliability of the following analytical efforts. This work was also conducted solely by myself. Furthermore, I carried out the validation process, where I assessed the soundness and accuracy of the calculated technical potentials in comparison with real-world monitoring data of large open-loop systems.

In the final step of my work, I translated the research into comprehensive written content resulting in the manuscript that was submitted to the scientific journal. Additionally, I prepared all figures and schematic visualizations of the publication. During the regular meetings within the GRETA-project, it was possible to establish an ongoing and fruitful exchange with my co-authors, which gave me important guidance. Finally, I prepared the answers to my reviewers and put major effort into improvements of the published version of the research paper.

City-scale solutions for the energy use of shallow urban subsurface resources – Bridging the gap between theoretical and technical potentials
Jannis Epting, Fabian Böttcher, Matthias H. Mueller, Alejandro García-Gil, Kai Zosseder & Peter Huggenberger
Renewable Energy
doi: 10.1016/j.renene.2019.09.021

CRediT authorship contribution statement: Jannis Epting: Conceptualisation, Methodology (3D-THM, Conceptual 3D-THM), Formal analysis, Data Curation, Writing, Visualisation, Funding acquisition; Fabian Böttcher: Conceptualisation, Methodology (2D-BM), Formal analysis, Data Curation, Writing, Visualisation; Matthias H. Mueller: Data Curation, Review & Editing; Alejandro García-Gil: Conceptualisation, Methodology, Review & Editing; Kai Zosseder: Conceptualisation, Review & Editing, Supervision, Funding acquisition; Peter Huggenberger: Review & Editing, Supervision, Funding acquisition.

Author Contribution: This publication was mainly a joint effort of Jannis Epting and myself. The abstract of the study is available in Chapter 5. Although I am not the first author of this publication, I nevertheless took the leading role in preparing the research that was conducted. My own contribution in the study encompassed in average 50% of the overall work, which was formally confirmed in writing by all of my co-authors. In the initial stages of the research, Jannis Epting and I shared the lead of the conceptualization phase, defining the study's scope and overarching goals. Methodologically, I played a pivotal role in designing the framework, specifically in the realm of 2D-BM methodology. This involved crafting a robust approach that linked the theoretical with the technical potentials of shallow geothermal usage.

Formal analysis was also a key facet of my contribution, wherein I conducted the analysis on the hydrogeological data of Basel for selected city quarters and carried out the joint evaluation of hydraulic and thermal potentials that formed the project's main findings. Data curation was another critical task I undertook, ensuring the assembly of a comprehensive and accurate dataset, which facilitated the project's analytical calculations.

Drafting the manuscript was again a joint effort of Jannis Epting and me. In detail, I particularly lead the writing of Sections 5.2.2, 5.3.1, 5.3.2, 5.3.4 and 5.4.2. I also had a leading role in data visualization and graphical representations comprising roughly 60% of the work conducted. Answering to the reviewers and improving the manuscript accordingly for resubmission in the peer review process was once again a team effort between Jannis Epting and myself. Therefore, I also want to thank the remaining co-authors for their contribution, which mainly comprised the phase of reviewing and editing and underscored the collaborative nature of this research.

Thermal influences on groundwater in urban environments –
A multivariate statistical analysis of the subsurface heat island effect in Munich
Fabian Böttcher & Kai Zosseder
Science of the Total Environment
doi: 10.1016/j.scitotenv.2021.152193

CRediT authorship contribution statement: Fabian Böttcher: Conceptualisation, Methodology, Formal analysis, Data Curation, Writing, Visualisation; Kai Zosseder: Conceptualisation, Review & Editing, Supervision, Funding acquisition.

Author Contribution: All critical phases of the research were conducted independently by myself. For a summary of the study, please refer to Chapter 6. My involvement commenced with the conceptualization phase, wherein I played the leading role in defining the study's scope and direction. Methodologically, I independently shaped the research framework, ensuring its robustness, accuracy and alignment with the objectives. Besides developing the methodology, my main work was evident in the rigorous examination of collected data, leading to the extraction of meaningful insights.

As data curation is not directly visible in the final publication, I want to emphasise this fundamental step of elaborate work here. The assembling of a comprehensive and accurate data set is crucial for a reliable subsequent analysis and was carried out independently by myself. In addition, my work cumulated in writing the manuscript, which comprises the textual representation of research outcomes and the data visualization, creating graphical representations and schemata. In addition, I integrated the comments and suggestions for improvement from my supervisor and reviewers in the peer review process.

I want to thank my supervisor Kai Zosseder, who's contributions were centred around critical oversight. As a co-conceptualizer, Zosseder provided valuable insights during study initiation. His role in review and editing elevated the quality of the work, ensured consistency, accuracy, and clarity. Zosseder's supervisory role was vital in guiding the project's progression, fostering collaboration among team members, and maintaining alignment with overarching goals. Additionally, Zosseder's engagement in securing funding was instrumental in providing the necessary resources for project continuity. The efforts of both authors underscore the collaborative and multidisciplinary nature of the project's success (see Section 6.6).

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Contents

List of Figures

List of Tables

Chapter 1

Introduction

In 2015, 196 Parties adopted the Paris Agreement with the goal of limiting global warming preferably to 1.5 °C, compared to pre-industrial levels (United Nations, 2015b; IPCC, 2018). Alongside, the General Assembly adopted the 2030 Agenda for Sustainable Development, which sets 17 goals for sustainable development (United Nations, 2015a). Within this objective, the access to affordable and clean energy is a key objective and an ongoing challenge for modern societies worldwide (United Nations). Policymakers recognised that a sustainable and secure energy supply for growing economies can only be accomplished by increasing resource efficiency and reducing the share of primary energy use. With the European Green Deal, the European Union (EU) set an ambitious roadmap to achieve at least 50% reduction of greenhouse gas emissions by 2030 compared with 1990 levels in order to become the first climate neutral continent with no net emissions of greenhouse gases by 2050 (European Commission, 2019). To cope with the European goals and the Paris Agreement, Germany substantiated its climate protection goals from 2010 in a climate protection plan in 2016 (BMU, 2016). In 2019, the national aims were strengthened by the climate protection program 2030 (Bundesregierung).

Especially a more efficient and sustainable heating and cooling sector can contribute significantly to meet the targets and reduces energy imports, as it consumes half of the European Union's energy (European Commission, 2016). In 2020, the EU-27 states had a 23% share of renewable energy sources in the gross final energy consumption for heating and cooling (Eurostat, 2022). This number is still below today's possibilities and can be improved by laying the foundation for an efficient use of renewable technologies. One controversially discussed decarbonisation strategy of the heating sector is its electrification with heat pumps. However, heat pumps lead to a trans-regional synchronous peak of electricity demand that does not correspond to a high production of electricity from wind or solar power (Thomaßen et al., 2021). A solution for this problem is not yet present, but it can be approached from two sides. One is the supply side, which can be improved by building seasonal storage capacities, and the other is the demand side, which can be decreased by installing the most efficient heat pumps (Born et al., 2022). Especially during the crucial peak load operation in winter, ground-coupled heat pumps supplied by shallow geothermal energy use a warmer heat source than air-sourced heat pumps and consequentially consume less electricity. Since the global climate is already in a crisis, actions to reduce greenhouse gases emissions have to be taken rapidly, and we need to make the most of every available option. Within the field of shallow geothermal energy, thermal use of groundwater is one of them.

1.1 Shallow Geothermal Energy

In Central Europe, the temperature rises by around 3°C every 100m, which is known as the geothermal gradient (Stober and Bucher, 2014). However, this means that you would have to drill relatively deep to reach adequately high temperatures for heating or much deeper for electricity production. Even modern houses with panel heating that runs at a low temperature of about 35°C would need to drill 830m deep for a direct use of geothermal energy. Obviously this is neither a practical nor an economical solution for the heating supply of single buildings. Boreholes with depths of kilometres that tap reservoirs of around 100°C are only feasible for larger heating grids that supply urban neighbourhoods. Such systems fall in the domain of deep geothermal energy (cf. Figure 1.1). However, there are also possibilities to utilise the geothermal energy that is stored in the shallow ground.

In the shallow ground, at depths of up to a four hundred meters, moderate temperatures ranging from $7-20$°C are present year-round (Stober and Bucher, 2014). In these layers the

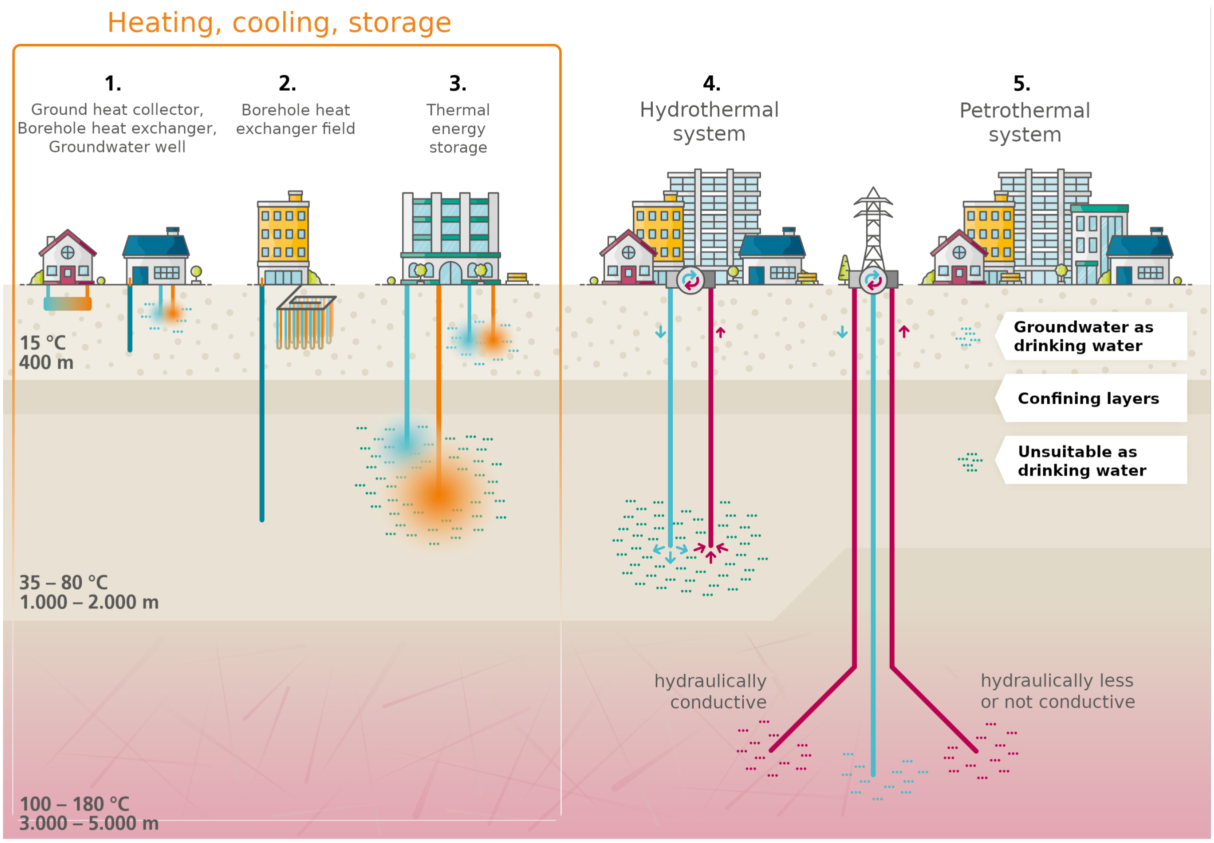

Figure 1.1: Geothermal systems for extraction and storage of thermal energy from shallow geological layers until 400m depth, singe systems for local heating grid supply and deep geothermal systems for the supply of large heating grids (modified after Born et al. (2022)).

thermal regime is primarily influenced by the energy flux of solar heat from the surface instead of geogenic heat (Banks, 2012). This effect is particularly noticeable in the upper ten to twenty meters, which represent the zone of seasonal temperature fluctuation. At those depths, we can still harness the stored geothermal energy for heating and cooling. Depending on the desired temperature, heat pumps or cooling units can efficiently enhance the geothermal energy source to achieve the required temperature levels. It can also be sufficient to utilise the shallow geothermal temperature directly for cooling. In buildings, the combination of heating and direct cooling is especially efficient, because minimal additional installations are necessary and electricity is only needed for the operation of circulation pumps. Apart from the standard use cases, shallow geothermal systems provide versatile and unobtrusive solutions for a wide range of heating and/or cooling demands, such as de-icing of transport infrastructure, cooling industrial processes or thermal energy storage (Eugster, 2007; Śliwa et al., 2016; Visser et al., 2015; Bauer et al., 2010; Lund and Boyd, 2016; Arthur et al., 2010).

So how can we harness shallow geothermal energy (SGE)? In general, closed and open systems are distinguished for utilising SGE (Stauffer et al., 2014). Closed systems consist of pipes placed in the ground as closed loops. A cooling agent is circulated in the pipes to extract energy conductively from the ground. The pipes can either be buried horizontally in the upper soil at a depth of a few meters, known as ground heat collectors (see Figure 1.2a), or they are cemented in vertical boreholes, known as borehole heat exchangers (see Figure 1.2b). In contrast, open systems use groundwater as heat carrier instead of a cooling agent and consist of wells to extract and inject the groundwater for thermal use (see Figure 1.2c). Following the natural groundwater flow direction, the extraction well is placed upstream from the injection well and

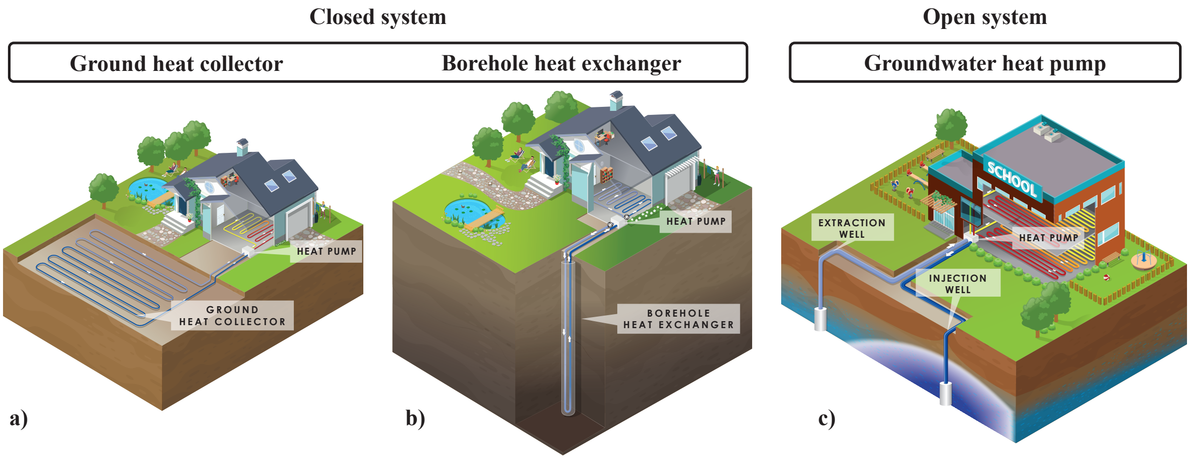

Figure 1.2: The main types of shallow geothermal energy extraction with a) ground heat collectors, b) borehole heat exchanger and c) groundwater heat pumps.

equipped with a submersible pump so that thermally unaltered water can be used throughout the operational phases.

As mentioned, the use of SGE relies on heat pumps that transfer heat from a lower temperature source to a higher temperature heat sink (ASHRAE, 2014). This is typically accomplished using a vapour compression refrigeration cycle which is driven by the mechanical energy of a compressor. The cycle consists of a low-pressure and a high-pressure side (ASHRAE, 2017). At the low-pressure side a heat exchanger, i.e. the evaporator, transfers the heat from the geothermal source to the refrigerant where it evaporates. Afterwards, the refrigerant gets compressed and enters the high pressure side as superheated vapour. At this elevated temperature level the refrigerant transfers the stored energy to the sink by passing a second heat exchanger. In the condenser, heat is exchanged with a consumer that may be the heating circuit of a building and the superheated vapour condensates. Finally, the refrigerant enters the low-pressure side through the expansion valve where the temperature drops considerably, and the cycle can restart at the evaporator.

The efficiency of heat pumps is determined by the amount of temperature rise, which the compressor has to generate from the source to the sink. Figure 1.3 exemplifies this dependency for two different source temperatures using the idealised Carnot efficiency. The Carnot efficiency describes the theoretical upper limit of performance for a compression refrigeration cycle. This is achievable under the assumption that the cycle is fully reversible and operates between two fluids at different temperatures, each with infinite heat capacity (ASHRAE, 2017).

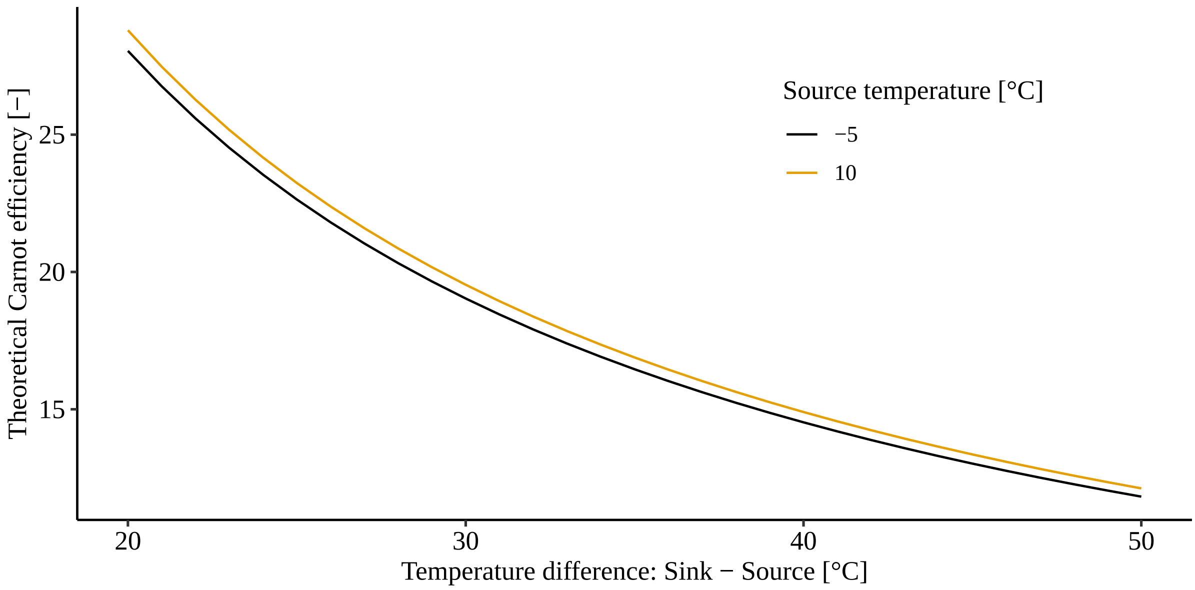

Figure 1.3: The theoretical Carnot efficiency of an ideal reversible refrigeration cycle for different temperature differences and source temperatures calculated by equation 1.1.

When the source temperature (T_c) and the sink temperature (T_h) remain constant, the Carnot efficiency (η) depicted in Figure 1.3 can be calculated using equation 1.1.

$$\eta = \frac{T_c}{T_h - T_c} \tag{1.1}$$

On the consumer side, this makes the application of heat pumps more attractive for newer or refurbished buildings, preferably with panel heating, because of a lower inlet temperature in the heating circuit. On the resource side, the temperature level of the source, i.e., air, ground, or water, determines the lower boundary for the resulting temperature difference in the heat pump This makes geothermal heat pumps generally more efficient than air-source heat pumps (Self et al., 2013; Urchueguía et al., 2008; Erb et al., 2004; Miara et al., 2011). In general, the use of SGE considerably mitigates greenhouse gas emissions by reducing the primary energy consumption and increasing the efficiency of primary energy use (Bayer et al., 2012; Blum et al., 2010; Saner et al., 2010; Fridleifsson et al., 2008; Schiel et al., 2016). Among geothermal heat pumps, groundwater heat pumps can theoretically achieve higher efficiencies than ground-source heat pumps because extraction and injection are thermally decoupled, resulting in higher source temperatures (cf. Figure 1.3). However, considering the system's overall efficiency, the higher electricity consumption of the submersible pump often compensates for the efficiency gain from the heat pump compared to efficient circulation pumps in closed loop systems (Miara et al., 2011). This disadvantage in the efficiency of groundwater heat pumps is reduced in shallow aquifers with a low depth-to-water.

The choice of SGE extraction system is not arbitrary but is subject to certain local constraints that typically determine the most suitable system. Several legal restrictions generally limit the usage of SGE, including nature protection zones, flooding zones, contaminated sites and drinking water protection areas (Zosseder et al., 2019). Horizontal closed loop systems benefit from loosely bedded soils with high thermal conductivity, which are easy to excavate and have a slope of less than 15 °(Bertermann et al., 2015).

In comparison, horizontal systems require more lateral space and rely on a permeable ground surface for precipitation to effectively regenerate the ground thermally during summer (Sipio and Bertermann, 2017). This limitation makes the use of horizontal systems challenging, particularly in urban areas where land plots are smaller. However, when sufficient space is available, horizontal systems are often an appealing option due to their lower installation costs and fewer legal constraints.

Vertical closed-loop systems require less lateral space because they are installed vertically in boreholes with drilling depths of up to several hundred meters in many regions. Borehole heat exchangers have the advantage of requiring minimal maintenance, and design values such as the thermal conductivity of the ground are well-documented in many European countries. However, compared to horizontal systems, vertical systems have higher installation costs, and drilling risks, such as evaporites, swellable rocks, karstic rocks, mining areas, or artesian aquifers, can impose constraints on drilling depth or even prohibit drilling entirely (Zosseder et al., 2018). In cases where multiple aquifer layers are present, the drilling depth is often legally restricted to the top of the first confining layer as a precautionary measure to prevent artificial hydraulic connections to lower layers, ensuring the protection of drinking water sources (Haehnlein et al., 2010; Zosseder et al., 2019). In ground with low hydraulic conductivity, borehole heat exchanger fields can be particularly suitable for energy storage or for providing both heating and cooling in an alternating manner (Reuss, 2015; Skarphagen et al., 2019).

The utilisation of open-loop systems is highly dependent on the local hydrogeological conditions. These systems can only be installed in regions where a sufficiently productive aquifer with suitable temperature and depth exists (Banks, 2009a; Lee et al., 2006; Milenic et al., 2010). Furthermore, the chemical composition of the groundwater should not cause corrosion or clogging in the heat exchanger on the source side. If the site is suitable for the thermal use of groundwater, particularly large open-loop systems can be more cost-effective during installation and more efficient during operation. This is because water has approximately double the volumetric heat capacity of the underground solid matrix, allowing for a significant amount

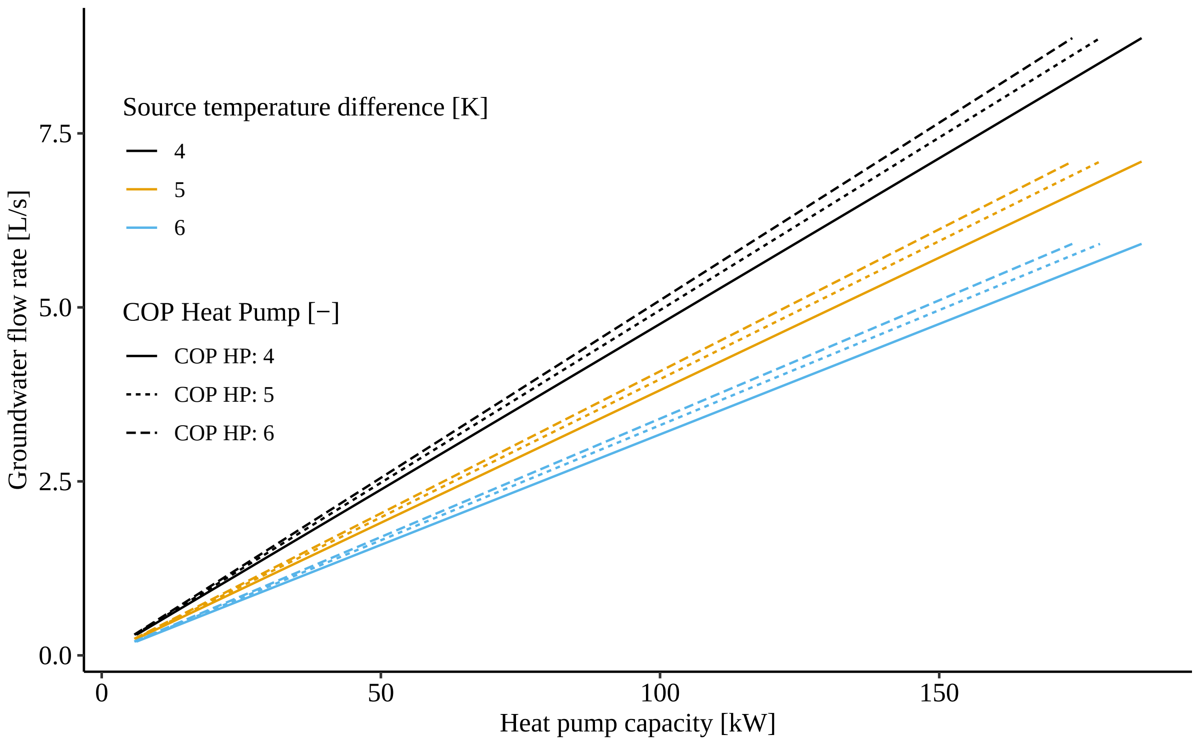

Figure 1.4: Required groundwater flow rate per heat pump output capacity for different coefficients of performance (COP) and temperature differences at the source-side heat exchanger.

of energy extraction with the typically permitted temperature difference of $5K$ in a heat pump (Zosseder et al., 2019).

As an example, a medium-sized extraction well capable of pumping $5L/s$ can provide approximately $105kW$ of geogenic energy with the usual $5K$ temperature difference. With a decent thermal conductivity of the ground, a borehole heat exchanger can deliver around $60W/m$ and horizontal ground heat collectors around $40W/m^2$ (VDI 4640 Blatt 2, 2019). This would require approximately $1750m$ of borehole heat exchanger or $2625m^2$ of buried collector pipes. Depending on the efficiency of the heat pump, the energy from the heat source is further increased by the input of electrical energy, resulting in the actual heat output to the sink (cf. Figure 1.4). The source energy can also be enhanced by increasing the temperature difference, if allowed by regulations (Haehnlein et al., 2010). Therefore, in areas with shallow and suitable aquifers, installing one extraction well and one injection well is usually the most cost-effective choice for supplying larger heating or cooling loads. However, the design of open-loop systems requires detailed knowledge of various hydrogeological parameters specific to the site. Certain parameters, such as the hydraulic conductivity of the ground, are particularly sensitive but often require extensive field experiments to obtain and may not be readily available in a decent spatial resolution (Fetter, 2001). As a result, there may be increased planning risks or higher exploration costs during a project's initial phase.

The mentioned uncertainties generally increase the initial investment cost and thus, hamper the use of SGE. The German SGE roadmap identified the lack of a comprehensive data basis and missing potential assessments as a key challenge for the further development of SGE (Born et al., 2022). Without the closing of those knowledge gaps geothermal heat pumps will fall short of their possible contribution to the electrification of the heating and cooling sector and subsequently to the reduction of greenhouse gas emissions. Thus, high quality and high resolution spatial datasets of design parameters are needed for tangible potential estimations. In addition, methods have to be developed that allow an appropriate spatial potential assessment which includes all relevant technical and regulatory constraints to support the expansion of SGE in the future.

1.2 The role of shallow geothermal energy in the decarbonisation of the heating and cooling sector

Political strategies already highlight the role of environmental heat, specifically heat pumps, in the building sector (European Commission, 2016). In the German energy efficiency strategy for buildings, heat pumps are recognized as having the second-largest potential for renewable heat production, positioned after biomass and before solar thermal energy (BMWi, 2015; Thamling et al., 2015). Efficient heat pumps are acknowledged as the most important key technology in all transition scenarios towards a decarbonised heating and cooling sector (Bade et al., 2014; Purr et al., 2019, 2021; Engelmann et al., 2021; Prognos et al., 2021; Fraunhofer IWES/IBP, 2017). Their primary limitation lies in their application in existing buildings with poor insulation and radiator heating systems (BMWi, 2015). Operating efficiently in such buildings poses a challenge, and building owners often do not opt for a heat pump without undertaking thermal refurbishment. Therefore, promoting refurbishment can also increase the adoption rates of efficient heat pump systems in existing buildings.

Ambitious scenarios for Germany project that approximately 18% of space and domestic hot water (DHW) heating demand will be supplied by heat pumps by 2030 (Engelmann et al., 2021). This implies the installation of around 6 million heat pumps, accompanied by a concurrent decrease in overall electricity demand in the building sector (Prognos et al., 2021). According to Prognos et al. (2021), the additional electricity required by heat pumps can be offset by replacing electric heaters and boilers with heat pumps, as well as by using more energy-efficient electric devices and lighting. However, grid operators are already calling for active and flexible regulation of heat pumps, as they introduce a relatively synchronised load on the electricity grid (Bundesnetzagentur, 2017). Active management would help distribute the load, thereby flattening the peak electricity demand on a daily basis. Additionally, it would provide the opportunity to increase the utilisation of electricity generated by intermittent renewable sources.

As mentioned earlier, one of the key requirements for the electrification of the heating and cooling sector is the efficiency of installed heat pumps. Geothermal heat pumps are generally considered more efficient compared to air-source heat pumps (see Section 1.1). However, the higher upfront investments associated with the more complex planning and installation process of geothermal heat pumps often make them economically unattractive. This drawback has gained attention from policymakers, leading to specific measures to promote the use of shallow geothermal energy (SGE) in energy strategies and incentives. For instance, the federal incentive program for efficient buildings in Germany provides increased funding rates for investment costs when utilising water, ground, and waste water sources (BMWK, 2022). Furthermore, both the European Commission and the German SGE roadmap propose certifications for installers of shallow geothermal systems and other renewable installations through accredited training programs (European Comissmion, 2021; Born et al., 2022). These initiatives aim to enhance the acceptance of SGE among installers, ensure higher quality planning, and lower costs through standardisation.

Standardisation and accurate system design rely on the availability of comprehensive planning tools that utilise detailed geological input datasets covering a wide spatial area. These tools should incorporate potential assessment methods that take into account all relevant technical and legislative constraints. The integration of detailed input data and comprehensive tools enables the generation of spatially differentiated results, considering both favourable and unfavourable local conditions. By conducting thorough potential assessments, it becomes possible to develop more nuanced and detailed local energy strategies, avoiding overly simplistic perspectives on the situation. This approach ensures that the planning process accounts for the specific characteristics and limitations of each location, leading to more effective and efficient utilisation of geothermal energy resources.

Spatial energy plans serve as a key strategic tool for municipalities to comprehensively evaluate heating energy demand and potential. The goal of sustainable energy planning is to optimise heat supply by considering all available and preferably renewable energy sources. In this context, spatial energy plans employ economic, environmental, and supply security criteria to conduct a comparative analysis of available energy sources, which serves as a basis for decision-making in developing strategies and action plans (Pohekar and Ramachandran, 2004). When it comes to heating and cooling, it is crucial for state-of-the-art potential assessments to include geothermal heat pumps and the utilisation of SGE for cooling. Integrating SGE into spatial energy plans would have a multiplier effect, as it would lead to the development of specific measures that consider the use of SGE in subsequently developed climate action plans. However, the GRETA project, which focused on the assessing potential of SGE in the Alpine space, found that detailed and specific analyses of the three main SGE systems are often missing in spatial energy plans (Zosseder et al., 2018). This is primarily due to the interdisciplinary nature of the topic, the time-consuming nature of data investigation, and the lack of quantitative potential assessment methods. This gap in analysis is particularly notable in the case of the thermal use of groundwater, despite the presence of highly productive and suitable aquifers in certain regions.

As new buildings continue to improve their insulation, the share of DHW demand in the overall heating load will increase. Since DHW demand remains relatively constant throughout the year and the SGE source is typically cooler than the ambient air during summer, air-source heat pumps become more competitive in modern single-home solutions (Fraunhofer IWES/IBP, 2017; Miara et al., 2011). This trend should be considered in energy plans by expanding potential evaluations towards larger applications, such as supplying low-temperature local heating networks or neighbourhood-scale solutions. Larger SGE systems, particularly the thermal use of groundwater, offer additional economic advantages as installation costs can be shared among multiple users. Local heating networks become more economically viable with higher spatial density of heating demand, making them an attractive solution for heating and cooling supply in urban environments and city quarters. Before implementing large-scale thermal uses of groundwater, it is crucial to understand the thermal regime of shallow aquifers beneath cities. In Munich, for example, there are already over 3000 registered thermal uses in the aquifer beneath the city. Therefore, a comprehensive potential analysis should consider the current usage and thermal influences on the aquifer. By gaining knowledge about the dynamic processes that govern the thermal regime of an aquifer, strategies for sustainable resource use can be developed, leading towards an integrated groundwater management.

1.3 Thermal influences on shallow groundwater in urban environments

The temperature of groundwater plays a crucial role in determining the energy potential stored in an aquifer and the efficiency of heat pumps that utilise groundwater as an energy source (see Section 1.1). Therefore, it is essential to understand the thermal influences on shallow groundwater bodies to conduct a comprehensive potential assessment of thermal groundwater use.

The urban subsurface is characterised by numerous anthropogenic influences and uses (von der Tann et al., 2020; Bartel and Janssen, 2016). These include extensive subsurface infrastructures such as train and road tunnels, sewer tunnels, rainwater drainage tunnels, deep buildings, communication cables, drinking water or rainwater retention caverns, gas grids, and heating and cooling grids. These subsurface infrastructures directly impact the thermal conditions of the ground in distinct and dynamic ways. In regions where cities are situated above productive and shallow aquifers, these subsurface uses further complicate matters related to groundwater, including drinking water protection, irrigation, and thermal utilisation (Menberg et al., 2013a). Additionally, the subsurface is influenced by surface thermal conditions and the developments occurring above the ground (Oke et al., 2017). To engage in scientifically based discussions on preserving the natural thermal state of urban groundwater bodies, it is crucial to properly understand the effects and intensities of processes that influence groundwater temperatures (Green et al., 2011). By comprehending the thermal influences on shallow groundwater bodies, it becomes possible to conduct a comprehensive assessment of the potential for thermal groundwater use. This understanding facilitates informed decision-making and supports the sustainable management of urban groundwater resources.

Originating from the surface, shallow ground temperatures naturally reflect the long-term average air temperature (Powell et al., 1988). Consequently, the subsurface is also subject to the effects of global warming, and temperature records in Germany indicate a trend of $0.4K$ warming per decade in the annual mean air temperature over the past 40 years (see Figure 1.5). This warming trend is also observed in soil temperature measurements from 55 stations in Southern Germany, analysed by the author for the period from 1987 to 2015 (GRETA, 2017). In a study by Kahlenborn et al. (2021), it is estimated that the southern and southeastern regions of Germany are particularly affected by warming, leading to an increase in the number of hot days and a decrease in precipitation. It has been demonstrated that such long-term climate regime shifts can have a significant impact on shallow and economically important aquifers (Menberg

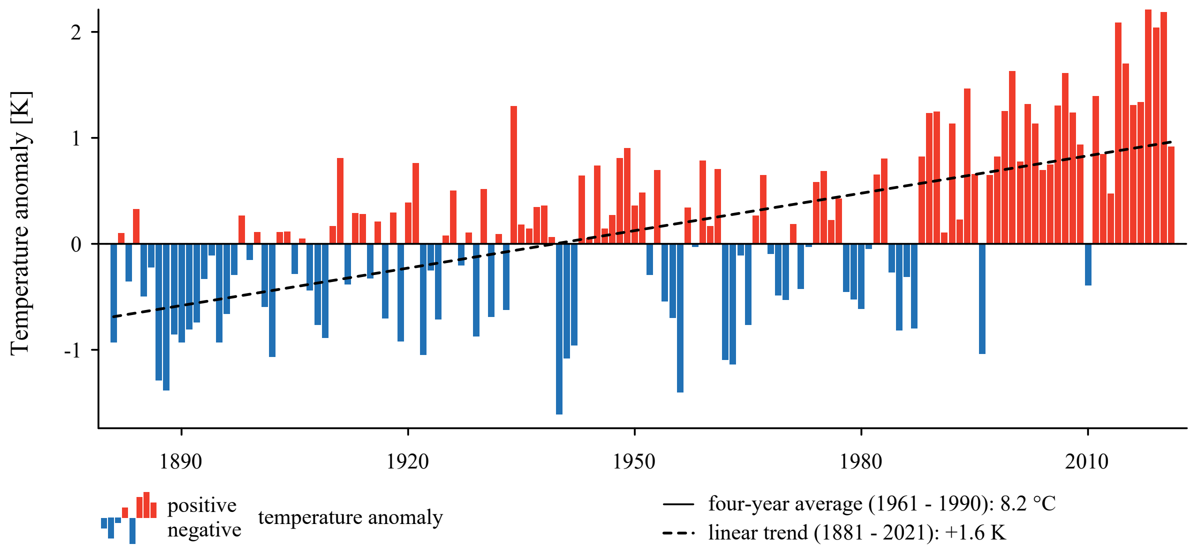

Figure 1.5: Annual mean air temperatures in Germany from 1881 to 2021 depicted as temperature anomalies referenced by the mean temperature of 8.2°C in the period from 1961 to 1990 (modified after DWD (2022)).

et al., 2014; Figura et al., 2011; Epting et al., 2021). Therefore, urban groundwater ecosystems face the combined challenges of climate change and the local influences of urbanization. These factors pose risks and uncertainties for the sustainable management of groundwater resources in urban areas.

While climate change is a steady and continuous influence on subsurface temperatures, additional heat from urban structures has been identified as the primary source of subsurface urban warming (Bayer et al., 2016). In densely urbanised areas where multiple buildings and infrastructure elements intersect, it is often challenging to identify the warming influence from a single source (Epting et al., 2017b). Only through the operation of temporally and spatially high-resolution temperature monitoring systems reliable analyses of influences from subsurface structures in the vicinity of measurements is possible. A study byBecker and Epting (2021) revealed the structural differences between the relatively continuous warming influence of underground parking lots and the seasonal dynamic influence of freeway tunnels. These findings emphasize the importance of conducting detailed studies on different subsurface structures to accurately characterise their influences. However, the long-term operation of highly developed monitoring systems is still rare, and a lack of knowledge regarding the thermal influence of subsurface structures under real-world conditions remains. Further research and monitoring efforts are needed to enhance our understanding of these influences and their implications.

Urban developments, whether they occur on the surface or subsurface, generally introduce heat into the ground and can lead to the warming of groundwater (Menberg et al., 2013a;

Mueller et al., 2018). The impact of temperature changes on aquifers, however, extends beyond simple thermal effects and can have complex chemical and biological implications (Jesußek et al., 2013a,b). Warming of groundwater is associated with several negative consequences for water quality (Green et al., 2011; Sharma et al., 2012; Hähnlein et al., 2013). These effects can be detrimental to the overall chemical status of groundwater. In fact, a report by the EU-27 countries from 2016 to 2021 indicates that 24% of the total groundwater body area already exhibits a poor general chemical status (EAA, 2020). Unfavourable thermal conditions resulting from future global warming are likely to exacerbate this situation and further contribute to the deterioration of groundwater quality.

In regions with a long history of urbanisation, soil and groundwater contamination is common, and a wide range of contaminants with diverse chemical properties can be present. Temperature variations can also have a significant impact on the flow and transport of pollutants. The temperature conditions can either facilitate or hinder specific chemical reactions and biological activities, thereby influencing ongoing processes (Bear and Cheng, 2010; Zheng and Bennet, 2002; Sprenger et al., 2011). Higher temperatures can enhance the mobility of contaminants by affecting sorption and solution equilibria (Brock et al., 2003). At contaminated sites, microbial biodegradation processes may be disrupted or the growth of harmful bacteria may be stimulated (Mackay et al., 1985). Therefore, understanding the energy balance of urban aquifers, including information on existing heat sources and sinks, is crucial for effective groundwater management strategies. By gaining a profound understanding of the thermal influence of specific heat sources, appropriate measures can be implemented to mitigate further temperature rise and preserve drinking water resources.

Furthermore, rising groundwater temperatures have a direct impact on the available potential for cooling, while the potential for heating increases. In a sustainable thermal management strategy, a balanced use of groundwater for both heating and cooling purposes would be advantageous. Thus, groundwater can serve as an energy storage reservoir, and different users can benefit from synergies (Epting and Huggenberger, 2013). An attractive option for balancing the energy budget of an urban aquifer is the increased use of groundwater heat pumps, particularly for heating purposes. Groundwater heat pumps not only contribute to restoring the natural thermal state of the aquifer but also benefit from higher efficiencies due to elevated source temperatures (Allen et al., 2003). In addition to thermal considerations, it is essential to address the specific requirements and constraints present in urban environments to ensure the sustainable growth of thermal groundwater use. These considerations will be discussed in the following section.

1.4 Thermal use of groundwater in urban environments

Cities have the highest heat demand density, making the transition of the heating & cooling sector in cities crucial for achieving a climate-neutral society. However, as addressed previously, densely populated areas present additional challenges for utilising groundwater for thermal purposes. Firstly, the cost of land in cities is high, limiting the availability of free space for potential well locations. Drilling rigs must be positioned on accessible construction sites while ensuring sufficient distance from neighbouring plots and buildings. Moreover, it is important to maintain an adequate distance between extraction and injection wells to prevent thermal recycling within the system. Unfortunately, these requirements are often not met in urban areas, and many plots of land do not allow for the minimum necessary well distance of 10 meters. When conducting spatial assessments of shallow geothermal energy (SGE) potential, it is crucial to consider these specific space requirements. This ensures that the analyses account for the diverse building structures found in different neighbourhoods within the city.

If sufficient space is available for well installations, an additional requirement to consider is the groundwater chemistry. Depending on the specific heat exchanger used, there are certain limits that must be met for oxygen saturation and content, pH value, iron and manganese content, chloride content, as well as free chloride. These limits ensure a sustainable operation of wells and heat exchangers without corrosion or clogging caused by unwanted mineral precipitation. While natural variations in groundwater chemistry, such as higher iron or manganese levels in bog regions, may occur, the geochemical composition of urban groundwater can also be altered by human activities. Consequently, conducting an initial chemical water analysis before commissioning is essential to prevent detrimental effects on the heat exchanger. However, if unfavourable chemical properties are already known, comprehensive potential assessment studies should properly highlight the operational risks associated with them. With the identification of adverse groundwater chemistry, appropriate technical measures can be implemented during the planning stage. For instance, the installation of an intermediate heat exchanger circuit can be considered to protect the heat exchanger within the heat pump and facilitate maintenance. Another measure that can be taken is the use of higher quality heat exchanger materials that are more resistant to the identified risks. Selecting materials that are specifically designed to withstand the anticipated conditions, such as corrosion-resistant alloys or coatings, can help ensure the longevity and reliability of the heat exchanger. By providing this information through potential assessments, the risks can be effectively managed early in the planning stage, reducing the likelihood of failure and maximizing the performance and durability of groundwater heat pumps.

In urban areas, in addition to the general geochemical conditions, there can be a wide variation of contaminants originating from industrial sites. In many countries, known contaminated sites are catalogued by the authorities, and in these areas, the thermal use of groundwater is typically prohibited to prevent the mobilisation of pollutants (Haehnlein et al., 2010). However, it is worth noting that in some cases, increased temperatures can have a beneficial effect on remediation efforts. The enhanced mobilisation of pollutants, due to higher temperatures can in turn catalyse microbial biodegradation processes (Brielmann et al., 2011). There have been observations of decreased waterborne pathogen concentrations in heat plumes generated by open-loop systems, suggesting that SGE utilisation can contribute to controlling bacterial contents in groundwater bodies García-Gil et al. (2018). Furthermore, studies have indicated that the mobility of heavy metals is not significantly influenced by increased temperatures, indicating that the use of SGE is not a driving factor in enhancing heavy metal contaminations (Bonte et al., 2013; García-Gil et al., 2016). These findings highlight the complex interplay between thermal use of groundwater, contaminant mobilisation, and potential remediation effects. Therefore, proper assessments and monitoring should be conducted to ensure the safe and responsible utilisation of SGE in areas with potential contaminant concerns.

As mentioned in Section 1.3, the thermal use of groundwater for heating purposes can help restore natural groundwater temperatures. However, in cities, there is also a substantial demand for cooling, and this demand is expected to increase significantly in the future due to the impacts of climate change (Frank, 2005; Davis and Gertler, 2015; Santamouris, 2016; Waite et al., 2017; van Ruijven et al., 2019; Li et al., 2019). Groundwater would be an ideal source for meeting the growing cooling demand, as direct cooling with groundwater is particularly efficient (Arthur et al., 2010; Urchueguía et al., 2008). Furthermore, integrating heating and cooling in the same system can lead to significant cost savings in overall installation expenses. However, the increasing demand for cooling in urban areas coincides with the anthropogenic warming of groundwater bodies beneath cities (see Section 1.3). This presents a challenging dilemma: to what extent is it acceptable to further increase the existing subsurface warming for the sake of reducing greenhouse gas emissions? This is a complex decision that requires careful consideration of various factors, including the magnitude of the subsurface warming, the potential environmental impacts, the effectiveness of alternative cooling solutions, and the overall goal of decreasing greenhouse gas emissions. It is essential to conduct thorough assessments and engage in informed decision-making processes to strike a balance between meeting the rising cooling demand and minimizing the environmental consequences.

Preserving groundwater quality for the protection of drinking water resources should indeed be the primary objective. To achieve this, it is crucial to have a comprehensive understanding of the potential harmfulness of temperature anomalies resulting from thermal groundwater use. However, the susceptibility of urban groundwater bodies to warming from thermal use is still not well understood (Epting and Huggenberger, 2013). This lack of understanding makes it challenging to conduct an objective scientific discussion on the topic. Additionally, there is currently a lack of detailed knowledge regarding the urban groundwater biocoenosis, i.e. the ecological communities of organisms, and their ecosystem functions. This scientific knowledge gap is reflected in the implementation of strong precautionary measures that restrict the thermal use of groundwater. For instance, the European Union Water Framework Directive defines the release of heat into groundwater bodies as pollution (Blum et al., 2021). However, several studies suggest that this view may be overly simplistic and could potentially be updated based on the steady scientific progress in this field of research. Certain studies have indicated that the thermal energy discharge below 20°C into uncontaminated, shallow aquifers poses no significant threat to ecosystem functioning and drinking water protection (Brielmann et al., 2009, 2011). Furthermore, moderate increases in temperature, ranging from 5 to 10K, have been found to cause only minor changes in water chemistry, microbial density, and ecosystem functioning in uncontaminated groundwater systems (Griebler et al., 2016). These findings highlight the need for further scientific research to better understand the potential impacts of thermal groundwater use on ecosystem functions and drinking water resources. As our understanding advances, it may be possible to refine the precautionary measures and regulations while still ensuring the protection of groundwater quality.

National regulations often impose limits on temperature changes concerning natural groundwater conditions, relative changes, or absolute values (Haehnlein et al., 2010). However, defining the natural groundwater temperature in urban areas is challenging due to the already mentioned complex interplay of various anthropogenic influences. In light of this complexity, regulations should take into account the specific conditions of urban aquifers and move away from static limits towards relative limits derived from existing background temperatures (Blum et al., 2021; Hähnlein et al., 2013). This task is challenging as it requires defining reference temperatures within the context of ongoing global warming and accounting for the spatial and temporal variability of urban temperature hotspots (Epting and Huggenberger, 2013). To develop appropriate regulations, it is essential to identify external factors that contribute to subsurface warming. This necessitates intensive monitoring of the subsurface to enable a comprehensive and ongoing thermal groundwater management. By incorporating these considerations into the regulatory framework, it is possible to better account for the unique characteristics of urban aquifers and the dynamic nature of subsurface temperatures. This approach allows for a more nuanced and context-specific evaluation of the impacts of thermal groundwater use, facilitating a balance between sustainable resource utilisation and the protection of groundwater quality.

During the approval process of new thermal uses in urban areas, authorities often face the challenge of adhering to the "first come, first served" principle in regulations (Haehnlein et al., 2010; Prestor et al., 2015). Many cities with productive aquifers already have numerous existing thermal systems that hold licences guaranteeing "undisturbed" groundwater temperatures for a specified period of time (Zosseder et al., 2019). Therefore, it is crucial that new installations do not negatively interfere with these already established systems. The warm or cold plumes that are discharged into the ground through injection wells can travel significant distances following the natural groundwater flow. If extraction wells from existing systems are located downstream within the thermally affected region, the efficiency of those systems can be considerably reduced. On the other hand, systems with an opposite type of thermal use (heating versus cooling) can benefit from favourable source temperatures, allowing them to reuse energy that was previously stored in the groundwater body. To address these potential negative interactions, regulations typically define a maximum allowable temperature change of $1K$ at existing extraction wells (Lo Russo et al., 2012; Piga et al., 2017; Pophillat et al., 2020; Molina-Giraldo et al., 2011; Umweltministerium Baden-Württemberg, 2009). However, evaluating potential negative interactions becomes increasingly challenging in complex urban environments where multiple thermal uses for heating, cooling, or combined systems coexist. Consequently, a comprehensive groundwater management approach is necessary to avoid unnecessary rejections of new installations due to a lack of knowledge and information on potential interactions. By adopting a comprehensive groundwater management strategy, authorities can better assess the potential impacts of new thermal installations on existing systems and make informed decisions. This includes conducting detailed hydrogeological studies, monitoring groundwater temperatures, and considering the spatial and temporal dynamics of thermal plumes. Such an approach minimizes the risk of negative interference and ensures the sustainable and efficient utilisation of thermal resources in urban areas.

In addition to the standard use of groundwater through extraction and injection wells, urbanisation presents opportunities for utilising SGE in innovative ways. New building projects in cities often involve structures that extend multiple stories underground, providing a large surface area that can be equipped with embedded heat exchanger pipes, creating passive energy absorbers. These thermo-active ground structures, such as energy piles, diaphragm walls, or concrete slabs, function similarly to closed-loop systems by extracting energy conductively through pipe loops (Brandl, 1998; Brandl et al., 2006; Brandl, 2016; Laloui and Di Donna, 2013). When considered early in the planning phase of a building project, thermo-active structures can offer an economic and integrated solution, particularly in areas with limited space. For buildings that extend even deeper into the ground, reaching the saturated zone and obstructing natural groundwater flow, culvert systems need to be constructed. Culverts are interconnected drainage pipes inserted upstream and downstream of impermeable barriers (e.g. deep buildings, tunnels, metro stations, or large sewers) to restore the natural flow gradient and prevent a significant rise in the groundwater table upstream. Typically operating without pumps, culverts utilise the principle of communicating vessels, allowing for the flow of a considerable amount of water. Therefore, existing culverts can be directly used for the thermal use of groundwater, eliminating the need for costly well installations (Epting et al., 2020). Since culvert systems are often connected to large public infrastructures like metro systems, the local energy supplier commonly acts as a central user of culverts. This makes larger thermal uses of culverts operated by the energy supplier particularly suitable for establishing low-temperature local heating networks. Taking a comprehensive view of the available resources and incorporating innovative technologies, such as thermo-active structures and culvert systems, allows for more efficient and sustainable utilisation of SGE in urban areas. Proper planning and integration of these technologies into urban development projects can contribute to the realisation of climate goals and the establishment of environmentally friendly heating and cooling systems.

Chapter 1 has provided an introduction to shallow geothermal energy (see Section 1.1) and its potential role in achieving decarbonised heating and cooling systems (see Section 1.2). It has also emphasised the specific challenges associated with the thermal use of groundwater in urban environments, including the urban heat island effect and limited space for well installations (see Section 1.3 and 1.4). Chapter 2 will provide an overview of the existing research landscape in the field of thermal groundwater use, highlighting its achievements and pointing out areas where further investigation is required. This comprehensive understanding will lay the foundation for subsequent chapters, which will delve deeper into specific aspects of thermal groundwater use and explore potential solutions to the challenges at hand.

Chapter 2

State of the art

This chapter guides the reader through the relevant research previously conducted in the scientific field of this thesis. The main goal is to assess the potential of thermal groundwater use in urban environments. The first step in this process is to capture the quantitative potential of the resource, considering all technical and regulatory constraints. Subsequently, it becomes necessary to explore the thermal regime of the resource to reveal its actual energy content and to gain information on the efficiency at which it can be used. Therefore, this chapter is structured accordingly. Firstly,the existing work on potential assessment concepts for open-loop systems will be reviewed. Secondly,the most important studies on the warming effect of cities underground, known as the *subsurface urban heat island* will be discussed. Based on the characteristics of these different studies, any shortcomings and current challenges in these two fields of research will also be highlighted. The following sections extend the state-of-the-art considerations of the presented publications in this thesis, but do not replace them. For an additional overview on the specific field of research, the reader is referred to Section 4.1 for further information on quantitative potential assessment of thermal groundwater use, Section 5.1 for further information on potential evaluation in urban areas, and Section 6.1 for further information on subsurface urban heat islands.

2.1 Quantitative potential assessment of thermal groundwater use

One of the main challenges in potential assessment involves determining an accurate potential that takes into account technical and legal limitations (see Section 1.4). It is crucial that the assessed potential offers broad applicability and is conservative, thereby rendering it useful in practice. Consequently, a robust potential estimate for the thermal use of groundwater in well-systems must consider all relevant factors pertaining to the extraction and injection of groundwater (see Section 1.1). Moreover, potential estimates need to be quantitative to be applicable in energy planning (see Section 1.2).

The primary objective of all quantitative studies on the potential of thermal groundwater use is to estimate well yield. Generally, the analysis of well productivity has a long-standing history in hydrogeological research. Consequently, a variety of analytical equations for different hydraulic settings and flow conditions have been established (Misstear et al., 2017). Owing to their straightforward application with spatial data in Geographic Information Systems (GIS), the use of analytical equations is particularly popular in spatial potential assessment studies

(Götzl et al., 2014; Casasso and Sethi, 2017a; García-Gil et al., 2015a). However, analytical calculations of drawdown in a well make several fundamental assumptions about the hydrogeological conditions in the aquifer (Fetter, 2001). Initially, it is assumed that the groundwater body is bounded on the bottom by a confining layer and all geological formations are horizontal with an infinite lateral extent, as well as homogenous and isotropic properties. Furthermore, the groundwater table is initially assumed to be horizontal, with all changes attributed solely to the radial and horizontal flow towards the pumping well. The observation wells and the pumping well are assumed to be fully penetrating, with the latter having an infinitesimal diameter and 100% efficiency. Lastly, it is assumed that Darcy's law holds true and that the groundwater maintains a constant density and viscosity. Following this, analytical calculations are introduced that have previously been applied in potential assessment studies for the thermal use of groundwater.

The initial two equations make an additional assumption of steady-state conditions during pumping, which simplifies the analytical calculations. A steady-state is achieved when the cone of depression around the pumping well is fully developed, and no additional drawdown occurs (Fetter, 2001). With Equation 2.1, Thiem (1906) developed the first analytical solution allowing for the calculation of an aquifer's transmissivity (T) using known drawdown (s) at a radial distance (r), a constant pumping rate (Q), and a known radius of influence (R). If the transmissivity is already known, this equation can also be used to calculate the drawdown at a specific distance from the well, based on a constant pumping rate. Logan (1964) introduced a further simplification of Thiem's equation by deriving a "typical" factor (c) for both confined and unconfined conditions. Thus, it is possible to estimate transmissivity using Equation 2.2 solely from a known pumping rate, aquifer thickness, and drawdown in the well (s_w). However, Logan (1964) stated that this equation should only be used to obtain preliminary approximations when sufficient data is lacking, due to the potential for significant errors.

$$s(r) = \frac{Q}{2\pi T} \ln \frac{R}{r} \tag{2.1}$$

$$s_w = \frac{cQ}{T} \tag{2.2}$$

The first analytical solution for the non-steady computation of drawdown caused by a pumping well was established by Theis (1935). Besides the basic assumptions, he presumed a fully confined and compressible aquifer with no source of recharge, in which water is released from the aquifer concurrently as the hydraulic head is lowered. To solve the Theis or non-equilibrium equation 2.3 with the well function $(W(u))$, the well needs to pump at a constant rate. Cooper and Jacob (1946) simplified the Theis equation by introducing the straight-line method for a single well discharging at a steady rate and further assuming that drainage through the porous media is negligible. The drawdown in a pumping well can be calculated using Equation 2.4, given a storativity (S), pumping time (t), well radius (r_w), and coefficient of the quadratic term of the Rorabaugh equation (C) (Casasso and Sethi, 2017a).

$$s = \frac{Q}{4\pi T} W(u) \tag{2.3}$$

$$s_w(Q) = \frac{Q}{4\pi T} \log(2.25 \frac{Tt}{Sr_w^2}) + CQ^2 \tag{2.4}$$

The analytical equations introduced are typically applied with a specific drawdown limit dependent on the aquifer thickness to ensure sustainable operation of the well. However, the least rigorous potential assessment approaches consider the entire saturated thickness as maximum drawdown (Muñoz et al., 2015; Javandel and Tsang, 1986). As this could lead to well depletion and considerable environmental harm, such as damage to vegetation and ground stability issues, the values obtained can only be categorized as theoretical potentials. Muñoz et al. (2015) used Equation 2.2 developed by Logan (1964) with a factor of $c = 2$ to calculate drilling meters for groundwater heat pumps designed to supply a fixed heating demand of a standard single-family house. Drilling meters are calculated by adding the drawdown to the depth-to-water with no drilling limit and then multiplying the result by two for a hypothetical well pair. In the area studied, the demand can always be met, and the drawdown is mainly dependent on the spatial distribution of high and low conductive sediments. However, the groundwater in the urban area of Santiago de Chile is generally at depths of $100m$ or more. Hence, Muñoz et al. (2015) failed to emphasize that groundwater heat pumps for single-family houses are typically not feasible for such extensive depths-to-water. First, the installation costs for deep wells are not justifiable for small groundwater heat pump systems and, second, the electricity demand of the submersible pump will render the entire system inefficient (cf. Section 1.1). A potential analysis without a fixed demand would have been more suitable for evaluating the maximum thermal aquifer potential. Subsequently, the utilisation of groundwater in larger systems for supplying low-temperature local heating networks, or even heat pump enhanced district heating grids, could have been discussed (cf. Section 1.2).

Another approach was utilised by Götzl et al. (2014) in the potential assessment of Vienna, Austria. In this study, a simplified version of equation 2.1 by Thiem (1906) was employed to estimate the maximum pumping rates of extraction wells, and to limit the drawdown relative to the mean and low water levels. Owing to the limited knowledge about the spatial variability of the highly significant parameter, hydraulic conductivity, 14 homogeneous areas were delineated across the city. Using a constant temperature difference at the source-side heat exchanger of $5K$ and the volumetric heat capacity of water, thermal power was calculated from the resulting pumping rate. Based on the thermal power, a classification of four system size intervals was defined. This provided an initial overview of the general feasibility of thermal groundwater use.

Subsequently, Götzl et al. (2014) developed an approach for spatial potential evaluation. For uniform usage, i.e., heat or cooling, a system is only allowed to extract a certain amount of energy that is replenished by heat flux from the surface and advective inflow through lateral groundwater movement within the system owner's plot of land. For balanced usage, i.e., heating and cooling, a hypothetical well field was positioned in the respective plot of land. Subsequently, minimum required distances between wells avoiding thermal recycling were determined by the extent of the depression cone. The cone sizes were calculated analytically using the equation by Sichardt (1928) and a global minimum distance of $25m$. However, despite mentioning well pairs, Götzl et al. (2014) did not carry out a specific positioning of injection wells or consider possible negative interactions between neighbouring systems in the case of balanced usage. Although a thermal balance is maintained throughout the year, considerable temperature anomalies can develop in the respective season, and the calculated extent of the depression cone will not guarantee sustainable operation of the assumed well field. In addition, the resulting differences between the energy-based and well-field-based assessment approaches are not detailed. The energy-based results show values that are 3-4 times lower than the well-field-based results. It remains unclear how the previously estimated maximum pumping rates are integrated into the energy-based evaluation. For instance, large plots of land with high energy fluxes might not be able to exploit the energy with one extraction well due to less favourable hydrogeological conditions. As an aggregated evaluation, the spatial approaches proposed by Götzl et al. (2014) already provide valuable decision support for the thermal management of groundwater in the five analysed study areas. However, for a plot-wise spatial analysis, important topics such as injection well positions or thermal recycling within a well pair are still not considered.

The specific topic of well spacing was addressed early on by Javandel and Tsang (1986) for the purpose of contaminant remediation using pump-and-treat methods. Using equation 2.3 by Theis (1935), Javandel and Tsang (1986) derived analytical solutions to calculate optimal distances between up to four pumping wells to prevent the escape of contaminated water. In this specific case, a complete drawdown of the saturated aquifer thickness was assumed. Even though the thermal use of groundwater was not the subject of the study, it nonetheless highlights the importance of adequate well spacing and the results can be discussed in relation to other approaches. The well distances calculated by Götzl et al. (2014) using Sichardt (1928) are consistently more than 10 times higher compared to those calculated by Javandel and Tsang (1986) in the two-well case. For the spacing of well pairs next to each other and perpendicular to the groundwater flow, the values from Sichardt (1928) can be considered very conservative. Conversely, the distances determined by Javandel and Tsang (1986) are stringent estimates, as the study's objective was to prevent the escape of contaminated water. Therefore, it becomes evident that a more refined view on spacings of multiple well pairs is necessary to properly constrain the thermal use of groundwater spatially.

A more rigorous approach for assessing the technical potential of extraction wells was developed by García-Gil et al. (2015a). In their study, a low-temperature geothermal potential (LTGP) was defined for both vertical closed-loop systems and open-loop systems determining the thermal power that can be abstracted from the geogenic energy source. For open-loop systems, the LTGP was calculated similarly to Götzl et al. (2014), using a temperature difference, the volumetric heat capacity of water, and an extractable groundwater flux. However, the temperature difference was not set as a constant value caused by a heat pump, but rather as a difference between the groundwater temperature and the annual average of the surface temperature. It has to be mentioned, that this approach is unsuitable for shallow aquifers, as the long-term average air temperature closely corresponds to the ground temperature below the zone of seasonal influence (Casasso and Sethi, 2016). As a result, the calculated temperature differences will be rather small and are not derived from technical or legislative constraints. Moreover, the spatial variation of the temperature difference is not documented in the study, and the applied values remain unclear. Consequently, a direct comparison of the LTGP results in different locations is challenging.

The second variable used to calculate the LTGP for open-loop systems is the flow rate that can be sustained in an extraction well. García-Gil et al. (2015a) computed the pumping rate using equation 2.1 by Thiem (1906), taking into account a radius of influence (i.e., $250m$ for unconfined conditions and $2500m$ for confined conditions) and a maximum permissible drawdown of 25% of the saturated aquifer thickness. In high transmissivity zones, the pumping rates surpassed realistic values. Therefore, a global maximum of $100L/s$ was applied to account for technical limitations in the pumping process. In conclusion, García-Gil et al. (2015a) incorporated the relevant hydraulic constraints necessary to define a conservative technical potential for open-loop systems. However, the method did not consider constraints of injection wells, sustainability issues arising from thermal recycling, or spatial hydraulic influences.

The most comprehensive assessment of technical potentials for thermal groundwater use was presented by Casasso and Sethi (2017a). The study accounted for both extraction and injection well constraints. Similar to García-Gil et al. (2015a), a drawdown in the extraction well was limited to 50% of the saturated thickness. Additionally, the rise in the groundwater table in the injection well was constrained in relation to the natural depth-to-water. A maximum rise of $3m$ below the ground surface was set as a safety margin to prevent flooding. This safety margin is particularly necessary in areas where knowledge about the hydraulic head is sparse or where considerable natural changes of the groundwater level is common. For the calculation of both drawdown and water table rise, equation 2.4 by Cooper and Jacob (1946) was employed, and the lesser of the two resulting flow rates for extraction and injection was used as the technical potential value. Due to the lack of high-resolution datasets of hydrogeological properties, Casasso and Sethi (2017a) were unable to perform a spatially continuous assessment and could only conduct point-wise calculations of open-loop potentials. Despite using the same analytic method for the calculation of rise and drawdown, the study pointed out that the results for both well types were obtained without considering their mutual hydraulic interference. This approach yields conservative estimates because the drawdown from a nearby extraction well would offset the groundwater level rise from an injection well, and vice versa. However, the study does not include a specific well distance from extraction to injection, or spatial considerations about well placement or hydraulic impact zones.

In summary, several studies have already developed quantitative potential assessment methods that integrate technical or legislative limits to ensure sustainable operation of open-loop systems. However, previous studies did not include all relevant limiting features for a comprehensive potential definition, nor did they utilise numerical methods to account for hydraulic interactions that occur within a standard two-well open-loop system. Furthermore, no previous study provided context on how the acquired potential results can be utilised in thermal groundwater management concepts or energy action plans, or how they should be adapted at different scales or compared with other SGE systems in an urban environment. In particular, within urban energy planning, it will be vital to provide comprehensive quantitative methods that address the relevant SGE extraction systems at varying levels of detail to ensure the future consideration of SGE. Beyond the technical and regulatory constraints that define the potential thermal use of groundwater, the specific thermal conditions within urban groundwater bodies govern the efficiency of heating or cooling supply and complement the assessment of the thermal resource. Thus, the next section focuses on research about the warming effect of cities in the subsurface.

2.2 Subsurface urban heat islands

As previously addressed in Chapter 1.3, the groundwater temperature determines the amount of stored thermal energy and governs the efficiency with which the energy source can be utilised. For a comprehensive potential evaluation of thermal groundwater use, a deeper understanding of the thermal regime in urban aquifers is necessary. Groundwater bodies beneath cities are subject to multiple thermal influences (cf. Figure 2.1). The complex interaction of these impacts typically results in a phenomenon known as the *subsurface urban heat island effect*. Different from the surface urban heat island, which is commonly abbreviated as SUHI in atmospheric sciences, the abbreviation SSUHI is used throughout this thesis. SSUHIs have been a focus of geological research for some time, as new heat islands are continually discovered through intensified monitoring efforts worldwide (Ferguson and Woodbury, 2004; Taniguchi et al., 2005, 2009; Yalcin and Yetemen, 2009; Gunawardhana et al., 2011; Menberg et al., 2013a; Lokoshchenko and Korneva, 2015; Bucci et al., 2017; Marschalko et al., 2018; Visser et al., 2020; Previati and Crosta, 2021).

After identifying the general presence of SSUHIs, the primary focus of research shifted towards determining specific causes for the warming in urban areas. However, early on, it was noted that the complex spatial variability of effects in urban environments led to a situation where the relationship between subsurface and surface processes and their influence on the SSUHI could not be easily determined (Ferguson and Woodbury, 2007). With groundwater flow, local temperature profiles become additionally complex and challenging to interpret, even if local flow conditions and heat sources are precisely known (Zhu et al., 2015). Therefore, simplistic relationships that use indirect characteristics of urban areas, such as the population density presented by Taniguchi et al. (2009), are inadequate to describe the complexity of SSUHI effects in shallow aquifers, as they fail to consider specific influences like groundwater flow. Similarly, radical averaging of heterogeneous depth-oriented ground temperatures, as presented in Taniguchi et al. (2005) and Taniguchi et al. (2007), does not account for the spatial variability of influential effects. This is especially the case when the observed temperature profiles are widely distributed across cities with significantly varying land use.

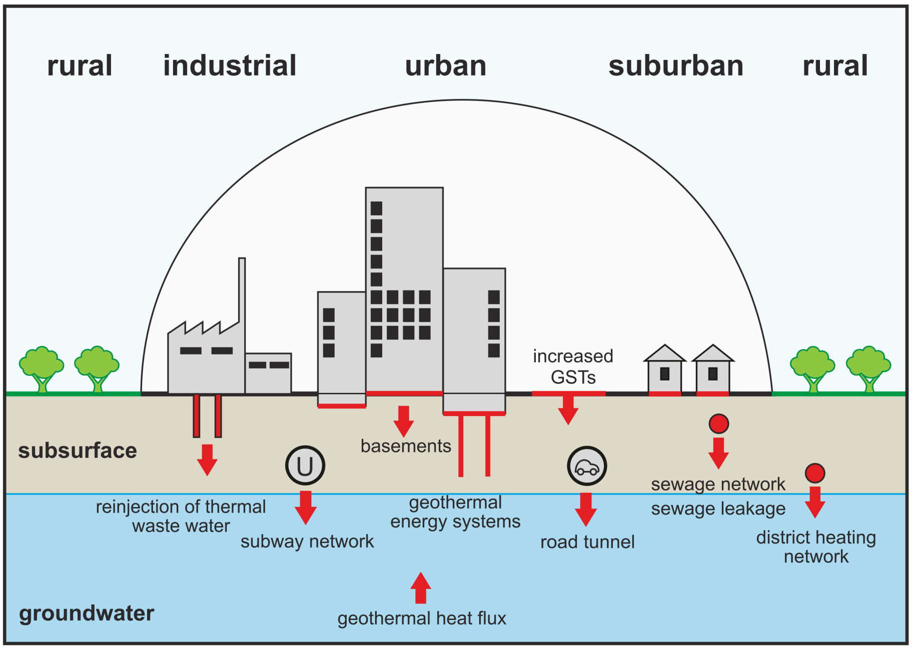

Figure 2.1: Potential anthropogenic and natural heat sources influencing the SSUHI (from Menberg et al. (2013a)).

Despite its necessity, comprehensive spatial and temporal temperature monitoring of urban groundwater bodies to capture the variability of SSUHI effects is uncommon. To overcome this lack of data, several research studies have aimed to establish a relationship between subsurface temperatures and more easily accessible satellite data (Green et al., 2011; Benz et al., 2016; Zhan et al., 2014b,a). In this regard, the Moderate Resolution Imaging Spectroradiometer (MODIS) temperature in its $1km$ resolution, made available through the Terra and Aqua satellites launched in 1999 and 2002 respectively, became particularly useful (Hulley et al., 2016; Zhengming and Dozier, 1996). Regarding different spatial datasets, Ferguson and Woodbury (2007) suggested and Benz et al. (2016) later demonstrated that ground surface temperatures (GST) should be preferred over surface air temperatures (SAT) when studying SSUHI effects. This is because GST already reflects anthropogenic changes to the landscape. Particularly in urban environments, where land-use varies on a small scale, the link between SAT and GST is not entirely understood. Huang et al. (2009) stated that SAT is likely to underestimate the SSUHI effect.

Although GST is more closely related to subsurface processes than SAT, utilising direct subsurface temperature measurements remains the optimal approach to study factors influencing subsurface warming. Given that the SSUHI effect is primarily a spatial rather than temporal phenomenon, distributed ground temperature measurements are needed to adequately capture the thermal regime beneath a city (Benz et al., 2017). This is especially necessary for shallow urban aquifers, as the advective heat transport through natural groundwater flow further complicates the study of influences that cause a SSUHI. In the following sections, the most relevant research on the governing or reducing influences on the SSUHI effect will be introduced and a critical evaluation of the input datasets used in the respective studies will be conducted.

In general, there is broad evidence suggesting that urbanisation and the accompanying anthropogenic changes in land-use are the primary and most evident causes of SSUHIs. Whether indirectly proven by correlating SAT to subsurface temperatures, as performed by Taniguchi et al. (2005), or directly demonstrated by calculating heat loss from buildings, as completed by Ferguson and Woodbury (2004), the cumulative warming influence from built-up areas was already apparent, even without spatially dense ground temperature datasets at hand. In more recent studies, knowledge regarding the relationship between elevated ground temperatures and the percentage of area covered by buildings has continually been refined (Benz et al., 2015, 2018; Previati and Crosta, 2021). Benz et al. (2018), using site-specific data from 15 temperature depth-profiles, concluded that the space and time resolution of the measurements is not sufficient for a comprehensive characterisation of the SSUHI in Osaka. Conversely, Benz et al. (2015) and Previati and Crosta (2021) based their analyses on continuous spatial datasets for groundwater temperature and various other parameters. This enabled them to conduct a detailed, city-wide analysis on the driving influences on the SSUHIs of Karlsruhe, Cologne, and Milan.

With the availability of spatial information on additional underground features, such as the sewage system, the subway, or the district heating network, more in-depth analyses became possible, and the influence of various features of urbanisation on SSUHIs could be evaluated more precisely. Consequently, a distinction between surface and subsurface anthropogenic influences was facilitated through higher-resolution data. Menberg et al. (2013a) conducted the first detailed study of six German cities, including Munich, utilising a large amount of underground temperature measurements, and qualitatively evaluated the potential anthropogenic and natural heat sources, as schematically summarised in Figure 2.2. For Munich, Menberg et al. (2013a) concluded that numerous local hot spots are observable and, as such, the SSUHI is likely controlled by many local and site-specific influences. However, identifying individual heat sources causing groundwater warming was still challenging. As depicted in Figure 2.2, the most substantial heat input is attributed to urban basements, followed by cooling systems of industrial sites. A further significant heat input was observed for subway and road tunnels as well as suburban buildings.

Gaining new insights into subsurface heat sources, Menberg et al. (2013b) developed an analytical heat flux model to further investigate individual drivers such as GST and the aforementioned subsurface influences. Using two separate groundwater temperature datasets from the years 1977 and 2011 in Karlsruhe, they were able to delineate these influences and compare their thermal impact quantitatively across the two time steps. For the 1977 temperature

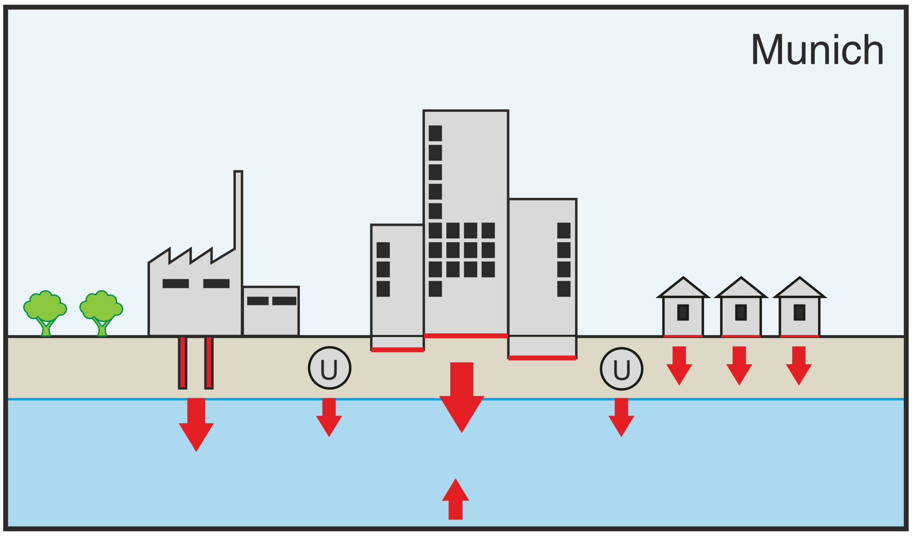

Figure 2.2: Schematic drawing of the identified dominant anthropogenic and natural heat sources in the subsurface of Munich. The thickness of the arrows indicate the strength of the heat source (from Menberg et al. (2013a)).

interpolation, 142 measurements were taken at the depth of the groundwater table, which lies 3 to 8*m* below ground. In 2011, 83 temperature measurements were available, taken at depths of 3 to 4*m* below the water table. Consequently, both temperature datasets are largely situated within the zone of seasonal fluctuations (refer to Figure 2.3). Thus, an interpolation of the collected temperatures within a year is only justifiable if the values are gathered within a relatively narrow time frame. Furthermore, the two datasets from 1977 and 2011 should reflect similar seasonal thermal conditions for a reasonable comparison. However, documentation or discussion regarding the influence of seasonal temperature variations is absent in the study. Thus, it remains unclear whether a substantial bias from differing seasonal conditions was present in the input data.

The evaluation of influential factors identified the GST as the dominant driver, followed by buildings - both of these parameters are surface-bound. However, it's worth noting that built-up areas, such as rooftops, are generally warmer than surrounding green spaces, meaning GST inherently reflects the spatial distribution of buildings. Therefore, in the analysis, the effect of buildings could potentially have been considered twice. GST can be regarded as a cumulative parameter that encapsulates all land-use associated effects, including the heat absorption of asphalt-covered streets or pavements. Given that GST was observed to be more dominant than buildings, indicates that the built-up area alone cannot fully account for the surface energy input, suggesting that additional information on surface-bound factors would be beneficial. Among the subsurface parameters, the district heating system was identified as the main source of thermal energy, closely followed by sewage leakage and the reinjection of thermal

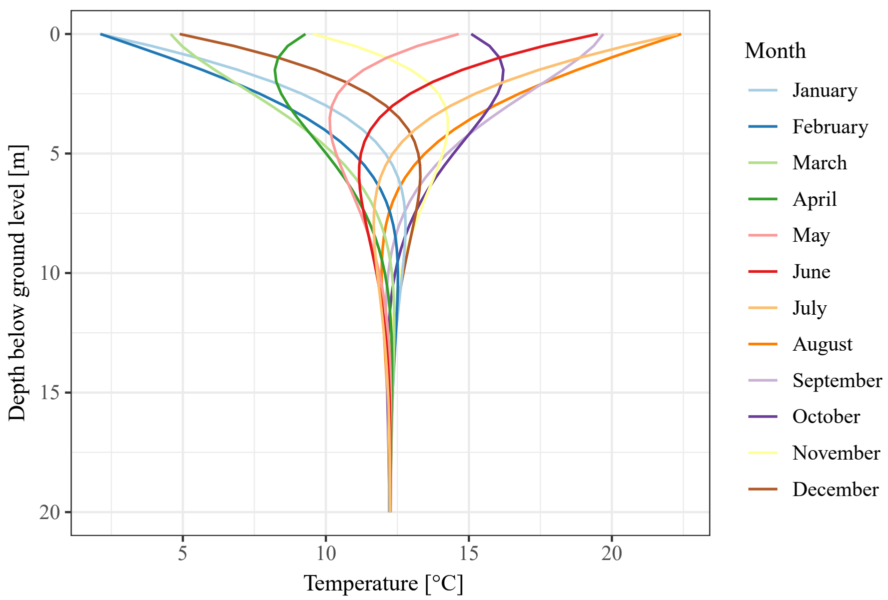

Figure 2.3: Typical calculated seasonal ground temperature profile in the City of Munich, Bavaria.

wastewater in 2011. The sewage system itself was found to be the least significant driver of the SSUHI in Karlsruhe.

The most comprehensive study of the SSUHI effect in a shallow aquifer, driven by field data, was published by Previati and Crosta (2021) for the City of Milan. This study area and overall approach share a thematic closeness to the research presented in this thesis, and will therefore be discussed in greater detail. In the City of Milan, temperature-depth profiles from 61 locations (acquired between June 2019 and September 2020 at five measurement dates) and 15 continuous data-logger recordings of hydraulic head and temperature allowed a detailed evaluation of natural and anthropogenic influences on groundwater temperatures. Contrary to previously discussed studies, Previati and Crosta (2021) observed a significant seasonal variation in the temperature recordings. To account for possible biases due to different seasonal conditions, the five temperature-depth profile measurements were interpolated over time, and the mean annual temperature at the water-table depth was used for further spatial correlation with 12 influential factors. However, the downside of this approach is that it only utilises a small portion of the available depth profile data, since a depth-dependent analysis of potentially changing influences in the spatial correlation was not included in the research.

Furthermore, Previati and Crosta (2021) did not incorporate the existing knowledge about groundwater flow directions into the spatial correlations of all influencing factors. Typically, temperatures recorded in observation wells are influenced by upstream conditions because Darcy velocities are relatively high in the studied aquifers, and advection is the dominant heat transport process. Instead, coverage data (i.e., the percentage of area covered by buildings, asphalt, railways, and green spaces) as well as the length of district heating pipelines were calculated over a circle with a radius of 500 meters. On the other hand, the preferable upstream distance along the main flow direction was measured only for underground tunnels. A third method was used to assess the potential influence of rivers or canals, in which the closest Euclidean distance was used as an indicator. Consequently, the results might be skewed by these different aggregation procedures. A possible indication for this could be the comparatively high Pearson correlation and steep regression coefficient observed for tunnels.

The design of the study conducted by Previati and Crosta (2021) also bears inherent challenges regarding the comparability of statistical results. As only straightforward correlations and linear regression analyses with one predictor were performed, only the direct influence of the specific predictor on the groundwater temperature can be assessed, but comparative statements about the 12 factors are impossible. Furthermore, the influence of potentially high spatial correlation among predictors remains unclear. Take the thermal use of groundwater for cooling as an example. This is more likely to occur in urban areas with a higher building density since more demand is present. Consequently, the increased groundwater temperatures observed in these areas might either originate from systems used for cooling or from buildings.

However, in the analyses performed by Previati and Crosta (2021), these distinct influences could become indistinguishable as they may be overshadowed by the locally dominant factor. This phenomenon of highly correlated predictors, known as collinearity, should be examined before drawing conclusions (Fox and Monette, 1992). This is particularly relevant when the spatial density of the studied factors simultaneously peaks within a 2-km-radius circle in the city where the SSUHI effect is detected (Previati and Crosta, 2021). Given this context, the most significant anthropogenic heat sources in Milan were identified as the percentage of building cover, surface sealing with asphalt and concrete structures, and the presence of underground tunnels and geothermal systems.

The study conducted by Epting and Huggenberger (2013) on the SSUHI effect in the City of Basel represents another comprehensive approach, where numerical groundwater modelling was employed. A 3-D flow and heat transport model of the shallow unconfined aquifer beneath the city was established and calibrated to the *present thermal state* using data from 32 observation wells. Various aspects of the urban environment were accounted for in the model. Subsurface infrastructure elements like building parts extending into the subsurface and thermal groundwater uses were geometrically represented in the model. Moreover, the anthropogenic changes in land use were included through the upper boundary condition at the ground surface. From a hydraulic perspective, this involved subdividing groundwater recharge zones based on the extent of surface sealing. From a thermal perspective, this entailed using measurements of soil and air temperatures. After calibrating the model to the *present thermal state*, all anthropogenic boundary conditions were subsequently removed to simulate a *potential natural state*. The resulting temperature field is presumed to reflect the thermal groundwater regime under undisturbed conditions and is used for analysing the SSUHI effect in Basel's aquifer.

Despite the considerable potential of large-scale groundwater modelling to integrate all relevant heat sources and sinks, such numerical models typically require substantial effort to calibrate accurately. Specifically, to interpret temperatures, both hydraulic and thermal calibrations are needed to correlate the simulation results with real-world measurements. However, the magnitudes of various energy sources or sinks are frequently unknown, and in some cases, their identification is the very objective of the research. As a result, it is challenging to accurately interpolate hydraulic and thermal soil properties spatially or to parametrise boundary conditions that have a significant influence on the SSUHI. With so many unknown variables, a high degree of uncertainty is inherent in the final calibration, as different parameter combinations can lead to the same simulation results. This is a characteristic of what is known in mathematics as "ill-posed" problem, and numerical groundwater models often fall into this category.

The approach adopted by Epting and Huggenberger (2013) to address this issue involved calibrating hydraulic conductivity, in-out transfer rates (for both flow and heat), and thermal soil properties. To examine the potential errors stemming from different calibration parameters, a sensitivity analysis was also carried out. The resulting sensitivities provide suitable indicators to quantitatively validate the significance of specific parameters. The study concluded by identifying two main anthropogenic factors influencing the SSUHI: the thermal use of groundwater for cooling and the increasing number of heated buildings extending into the aquifer. However, the authors emphasised that only the cumulative thermal influence of anthropogenic impacts could be replicated. This cumulative influence could be further dissected by enhancing the monitoring of thermal groundwater use and subsurface constructions and by incorporating the sewage network into the study.

Indeed, summarizing the current research on SSUHI in shallow aquifers, it's clear that the delineation of influencing factors, whether natural or anthropogenic, is a complex task. Both approaches (i.e. the statistical as presented by Previati and Crosta (2021), and the numerical as published by Epting and Huggenberger (2013)) underline the need for more extensive monitoring efforts and the current insufficiency of data to adequately depict this highly dynamic and heterogeneous phenomenon. In particular, studies focusing on the zone of seasonal temperature fluctuations face challenges due to a lack of long-term measurements. Without these, it's difficult to reduce potential distortions in the analyses caused by varying timing of measurements. Therefore, continuous and systematic collection of data is crucial for a deeper understanding of the SSUHI phenomenon, including its temporal variability and contributing factors. In light of the aforementioned review of the current state of research on SSUHI in shallow aquifers, this thesis aims to comprehensively assess the potential of thermal groundwater use in urban environments by addressing the identified knowledge gaps and enhancing our understanding of this complex phenomenon.

Chapter 3

Aims, objectives and structure of the thesis

Building upon the research gaps identified in Chapter 2, this chapter will articulate the aims and objectives of the three publications comprising this thesis. In alignment with the structure of Chapter 2, the first section will introduce the goals of the research concerning the potential assessment for thermal groundwater use, which is presented in Chapter 4. Subsequently, the objectives of the study on city-scale solutions for the energy use of shallow urban subsurface resources are elaborated, which forms the content of Chapter 5. Lastly, we will outline the research questions and objectives of the study on driving and reducing factors of the SSUHI effect in Munich, covered in Chapter 6. The following sections will detail the aims and objectives of these three publications, as integral parts of this cumulative thesis, and will explain how they are thematically interconnected.

3.1 Method development for the evaluation of a Thermal Aquifer Potential

As mentioned in Section 2.1, several studies have identified critical characteristics that restrict thermal groundwater use. Briefly, these limitations encompass three constraints: drawdown in extraction wells, water level rise in injection wells, and the recirculation of water between both wells. Previous research has not yet accounted for all of these limiting factors, nor was a consistent method developed that addresses the hydraulics of entire well doublets. Furthermore, no method has been proposed that is adaptable for use at various scales of interest. A comprehensive integration of open-loop potentials into spatial energy planning, however, requires assessments ranging from the aquifer scale down to the individual plot scale.

Therefore, the goal of this study was to develop a quantitative method for assessing the technical potential of thermal groundwater use, suitable for application in energy planning. The method aimed to incorporate relevant legislative and operational constraints to estimate achievable flow rates in well doublets, thereby enabling the calculation of site-specific extractable thermal power. Additionally, the approach aimed to facilitate spatial analyses by considering the hydraulic footprint of a well doublet, i.e., the area influenced by drawdown and water level rise. Finally, the potential assessment results for a real-world case study area should be validated by comparison with monitored existing thermal groundwater uses, providing a reference for the method's applicability. The development and application of this method in the city of Munich are covered in Chapter 4, which contains the publication titled

"TAP – Thermal Aquifer Potential: A quantitative method to assess the spatial potential for the thermal use of groundwater".

3.2 Method development to bridge the gap between theoretical and technical potentials

As outlined in Sections 1.4 and 2.1, an integrated approach to potential evaluation and groundwater management in urban settings should consider various extraction systems and existing infrastructure. Except for closed-loop systems, city-scale potential assessments of shallow urban aquifers are seldom conducted. Nonetheless, comprehensive thermal management of the subsurface should take into account the diverse options for resource usage, and evaluations should focus on defining technical potentials rather than theoretical ones.

In line with this, the objective of the work presented in Chapter 5 is to develop an initial approach to managing thermal resources in the urban subsurface. This is to be achieved by applying a combination of existing methods at different levels of scale. At the city-scale, the approach aimed to employ a 3D thermal-hydraulic groundwater model exploring the spatio-temporal development of groundwater abundance and advective energy transport. For 18 selected city quarters, the objective was to utilise the TAP-method (as presented in Chapter 4) quantifying feasible extraction rates and hydraulic impact zones of well doublets. The combined evaluation of these two approaches is intended to bridge the gap between theoretical city-scale energy potential assessments and technical strategies for GWHPs at the scale of city quarters. Additionally, a comparative analysis of 'active' (GWHPs) and 'passive' (energy absorbers within building envelopes) geothermal applications is to be conducted through feasibility indicators. These indicators should enable the evaluation of the potential for different geothermal applications in the various city quarters. Lastly, implications pertaining to potentially contaminated sites and existing thermal uses are to be discussed at the city quarter scale. The entire publication, which synthesizes the various potential assessment approaches, is encapsulated in Chapter 5, titled *"City-scale solutions for the energy use of shallow urban subsurface resources – Bridging the gap between theoretical and technical potentials"*.

3.3 Thermal influences on groundwater in the urban environment of Munich

As outlined in Section 1.3, understanding the temporal dynamics of temperature influences on groundwater is essential in defining the actual thermal potential that is available for seasonal heating or cooling demands. As stated in Section 2.2, studies examining the SSUHI effect in shallow aquifers often fail to consider the influence of seasonal temperature oscillations in their datasets. Moreover, the high-quality data on influential factors and groundwater temperature required to capture the dynamics of this highly variable process are often unavailable. Particularly, spatial datasets on hydrogeological conditions are necessary to conduct analyses that take into account the direction of groundwater flow, as it dominantly influences heat transport in highly conductive aquifers.

In order to address these challenges, the aim of the study presented in Chapter 6 is to identify the dominant drivers of the SSUHI at both local and large-scale levels in Munich. Given the extensive spatial datasets available for this study site, a multivariate statistical analysis will be performed for both natural and anthropogenic factors. The available depth-dependent temperature measurements are intended to serve as a basis for revealing vertical changes in the magnitude of natural and anthropogenic influences. Additionally, the study aims to develop an approach that incorporates spatially continuous data, such as interpolated groundwater thickness or surface sealing, as well as locally discrete data, such as heating grid or tunnels. The approach for continuous and discrete data should consider the high-resolution data on groundwater flow direction for a refined study of thermal influences based on their hypothetical origin. Furthermore, a specific goal of the research is to investigate the seasonal fluctuations in the shallow gravel aquifer in Munich using multi-annual groundwater temperature time series. This should provide deeper insight into seasonal behaviours, and a method should be developed to allow for the compensation of seasonal shares in differently timed measurements. The findings and analyses that address these objectives are presented in the publication titled *"Thermal influences on groundwater in urban environments – A multivariate statistical analysis of the subsurface heat island effect in Munich"*, which is included in Chapter 6 of this thesis.

Chapter 4

TAP - Thermal Aquifer Potential: A quantitative method to assess the spatial potential for the thermal use of groundwater

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Abstract

This paper proposes a method to assess the potential for thermal use of groundwater and its integration in spatial energy planning. The procedure can be adapted to local regulatory and operational limits, thus estimating legally and technically achievable flow rates and subsequently, the thermal power that can be exchanged with the aquifer through a well doublet.

The constraints applied to flow rates are *i*) a drawdown threshold in the extraction well, *ii*) a limit for the groundwater rise in the injection well and *iii*) a threshold to avoid the hydraulic breakthrough between the two wells. For the spatial assessment, the hydraulic influence on neighbouring well doublets is simulated with the maximum flow rates before the hydraulic breakthrough occurs. The Thermal Aquifer Potential (TAP) method combines mathematical relations derived through non-linear regression analysis using results from numerical parameter studies. A demonstration of the TAP method is provided with the potential assessment in Munich, Germany. The results are compared with monitoring data from existing open-loop systems, which prove that conservative peak extraction estimates are achieved.

Keywords : shallow geothermal energy, open loop, groundwater heat pump, geothermal potential, energy planning, water-energy nexus

4.1 Introduction

The European Union (EU) has set ambitious goals to reduce greenhouse gas emissions, increase the share of renewable energy (to 32% in 2030) and improve its energy efficiency (EU, 2018). Given that heating and cooling accounts for 50% of the EU's energy needs, any efficiency improvement in this sector will contribute significantly to reaching those targets. In particular, the use of shallow geothermal energy (SGE) mitigates greenhouse gas emissions by reducing the primary energy consumption and hence increasing energy efficiency (Self et al., 2013; Bayer et al., 2012; Blum et al., 2010; Saner et al., 2010). Thus, geothermal heat pumps can provide a strategic contribution in the de-carbonization of the heating and cooling sector (Fraunhofer IWES/IBP, 2017; Umweltbundesamt, 2017; Hans-Martin Henning and Palzer, 2015).

SGE can be used through open loop systems, which exchange heat with groundwater by means of a heat pump, commonly known as groundwater heat pumps (GWHPs). Separate wells are installed as a doublet to extract water from a shallow aquifer and re-inject it after thermal exchange (Stauffer et al., 2014). In consequence, the availability of groundwater in a sufficient quantity, quality, temperature and depth is the requirement for a sustainable operation of open-loop systems (Lee et al., 2006; Banks, 2012; Milenic et al., 2010). This makes the thermal use of groundwater a renewable, but spatially limited resource with a greatly varying availability (Ferguson and Woodbury, 2006; Fry, 2009). Detailed knowledge about the local hydrogeology and the resulting technical potential is crucial, for the installation of efficient open loop systems (Busby et al., 2009). If not available, cost-intensive exploration, like the drilling of observation wells, the conduction of well tests and time-intensive data inquiry can hamper the diffusion of GWHP systems (Pezzutto et al., 2017). Therefore, spatial potential evaluations for the thermal use of groundwater are key to identifying suitable areas and to fostering its use (Vienken et al., 2015).

The legislative procedures for licencing SGE systems commonly follow the "first come, first served" principle (Prestor et al., 2015; Epting and Huggenberger, 2013). However, a development of procedures towards active resource management would support authorities in the implementation of energy strategies (van der Gun et al., 2016; Alcaraz et al., 2017). Spatial potential evaluations serve as a data basis on which those management concepts can be built and on which approval decisions can be made (Alcaraz et al., 2016a).

The already intensive thermal use of groundwater in suitable areas, like Munich, shows how SGE resources have become relevant and should be taken into account in any energy development scenario (Urchueguía et al., 2014). In detail, assessment concepts have to provide quantitative extraction values at the smallest scale of urban energy planning, which assure a sustainable operation within legal and technological boundaries (Schiel et al., 2016). Previous studies, listed in Table 4.1, already identified the most relevant issues that constrain the potential of GWHPs. However, no study included all of them, nor did they use a uniform numerical

Table 4.1 Studies on the quantitative potential assessment of thermal groundwater use with applied constraints. *(share of saturated aquifer thickness)

Study	Drawdown	Breakthrough	Rise	Spacing
Bezelgues et al. (2010)	⅓* and max. 5 m	-	qualitative	-
Casasso and Sethi (2017a)	50 %* (Cooper & Jacob)	-	max. 3 m below surface	-
García-Gil et al. (2015a)	25%* and 100 L/s (Thiem)	-	-	-
Götzl et al. (2014)	Mean and low mean (Thiem)	-	-	-
Javandel and Tsang (1986)	100%* (Theis)	-	-	complete capture zone
Muñoz et al. (2015)	100%* (Logan)	-	-	-
Groupe de travail PDGN (2010)	-	-	-	thermal anomaly (GED)
Urich et al. (2010)	-	5% inter-flow & 0.5K feedback (HST3D)	-	thermal anomaly (HST3D)

or analytic method to perform a potential assessment per plot of land. Further, the defined constraints have to properly address the relevant issues on the specific scale of assessment. For example, on a single plot multiple well doublets would rather be aligned perpendicular to the groundwater flow to avoid thermal interference. Thus, the influence of doublets to the side will be more relevant than the extent of thermal anomalies downstream. Concepts for closed loop systems are already capable of detailed quantitative potential estimation with an application in energy planning (Ondreka et al., 2007; Casasso and Sethi, 2016; Santilano et al., 2016; Alcaraz et al., 2016b; Galgaro et al., 2015; Bertermann et al., 2014), whereas the open loop potential has not yet been assessed with all identified requirements.

This paper presents a quantitative method to assess the technical potential of thermal groundwater use for an application in spatial energy planning. The method integrates the relevant regulatory and operational constraints for an estimation of technologically achievable flow rates in well doublets and hence of the thermal power, which can be extracted at a specific site. The following Section 4.2 presents the assessment concept and the methodology. Section 4.3 addresses an exemplary application in Munich with a comparison between the TAP results and monitoring data in Section 4.3.3. Subsequently, the derived method as well as its assumptions and limitations are discussed in Section 4.4 with reference to the studies introduced in Table 4.1.

4.2 The TAP methodology – a legislative-operational potential

In the following, the TAP method is presented. First, the general approach is introduced to define the scope of the potential assessment (Section 4.2.1). Second, the numerical approach (Section 4.2.2) is explained to provide the basis for the mathematical formulation of the technical flow rate equations (Section 4.2.3) and finally, the hydraulic footprint of a well doublet is studied to deliver values on appropriate well spacing (Section 4.2.4).

4.2.1 General approach of the potential assessment

The major challenge in geothermal potential evaluation is the deduction from a theoretical (natural) potential to a more applicable estimation, which includes technological, legal and economical barriers (Rybach, 2015; Bayer et al., 2019). In addition, a potential estimation should have a high general validity to make it practically useful and sufficiently conservative. Since costs and subsidies are temporally and locally more variable than e.g. regulatory elements (Blum et al., 2011), an economic potential assessment is not in the focus of this study.

The approach integrates constraints within several steps. First, the legislative framework is reviewed to obtain the spatial restrictions of water protection areas and drilling limitations, as well as system related restrictions, like temperature, abstraction, drawdown and injection limits. Second, operational limits are defined with safety margins according to common practice, e.g. minimum injection of 4°C-cold water. All identified issues limiting the technical potential, as summarised in Table 4.2, are merged to evaluate a sustainable (technical) flow rate potential. Subsequently, it can be used to calculate the extractable thermal power with approvable temperature differences as well as absolute minimum and maximum injection temperature limits,

Table 4.2: Potential definition and limits related to open-loop systems.

Limitations	**Theoretical Potential**	**Technical Potential**	
	Physical limits	Operational limits	Regulatory limits
Hydraulic	Total volume of groundwater	Tolerable drawdown	Tolerable drawdown
		Drilling limits	Drilling limits
			Surface or basement flooding
Thermal	Ground energy budget	Min. injection temperature	Drinking water protection
		Thermal breakthrough	Max. injection temperature
			Max. temperature difference

i.e. 4°C and 20°C in the case of Munich. With the assessment results, the potential of thermal groundwater use can be integrated into energy planning at the building scale. Since the initial potential estimates follow the previously mentioned "first come, first served" principle, possible negative influences on neighbours are not yet considered. Instead, a maximum extraction per plot or raster cell is provided within legal boundaries (cf. Section 4.3.2). This strategy is also proposed for the first stage of licence application in recent SGE management concepts (García-Gil et al., 2015b). The following Section 4.2.2 describes the modelling approach to derive a functional dependence for the respective constraints.

4.2.2 Numerical modelling concept

For a comprehensive consideration of influential parameters, a numerical approach under the same simplifying assumptions is used. Therefore, idealised finite-element models are built, to determine the relevant influences on achievable groundwater flow rates in parameter studies. The simulations that vary the significant parameters against each other are conducted in idealised box-models with the following characteristics:

1. Vertically averaged flow was computed in 2D, according to the third level model reduction by Diersch (Diersch, 2014).
2. Unconfined flow and heat transport is simulated in steady-state.
3. The saturated groundwater thickness, the hydraulic conductivity and gradient are kept constant throughout the model domain.
4. The pumping rates are constant and the absolute values are equal for well doublets, while the wells are always fully penetrating the aquifer.

Fig. 4.1a shows the design of the numerical 2D-box-model and its boundary conditions. The model represents all material and geometric properties in an isotropic and constant way. The extraction and injection wells are located in the centre of the model, parallel to the groundwater flow at varying distances. The variation ranges of significant parameters are set according to their distribution in the study area, as shown for Munich in Table 4.3.

Table 4.3: Parameter ranges and number of cases used in the scenario variations for Munich.

Parameter	Unit	High	Low	Cases
Aquifer thickness	m	30	1	6
Hydraulic conductivity	ms^{-1}	$5.8 \cdot 10^{-2}$	$2.1 \cdot 10^{-4}$	6
Hydraulic gradient	-	0.01	0.001	6

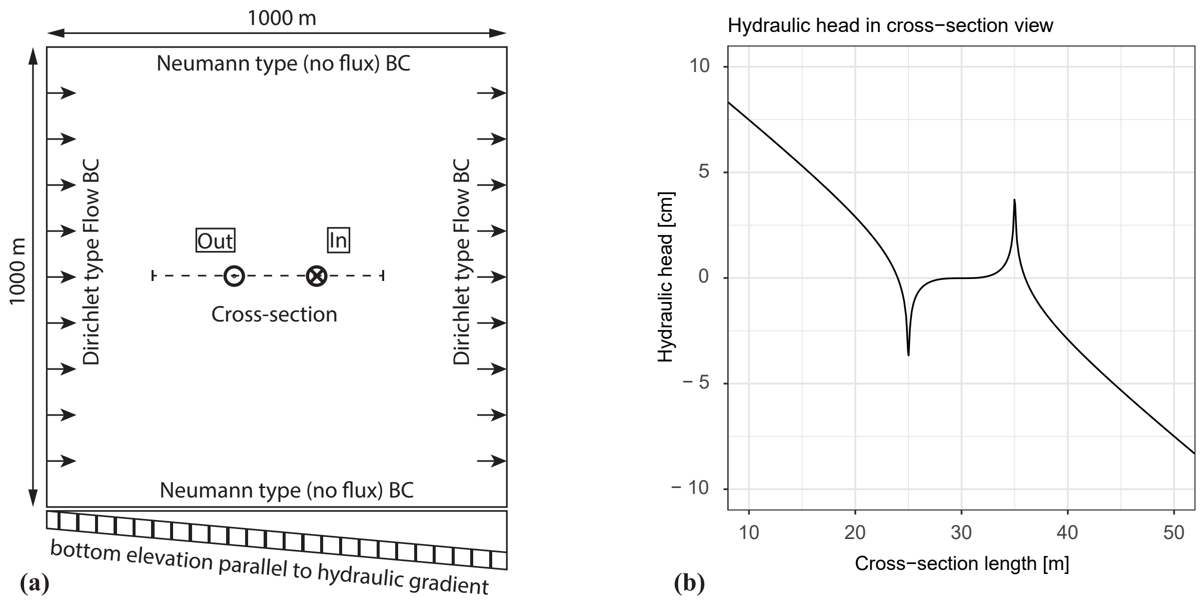

Figure 4.1: (a) Top-view and theoretical side view of the 2D box-model for flow simulation with boundary geometries; Out: Extraction well, In: Infiltration well and line of cross-section. (b) Hydraulic head along the cross-section at 10m well distance for simulated breakthrough threshold conditions.

For an application in other areas, where certain parameters might not be spatially known, ranges can also be derived from representative local measurements or literature values. Scenarios for the variations are given by the Cartesian product, which is composed of the respective set of significant parameters. Subsequently, the simulation results serve as a basis for a non-linear regression analysis to fit the mathematical formulations of the TAP method, as presented in the following sections (Bates and Watts, 2007). With an estimation of regression functions, an integration of the assessment procedure in existing GIS-workflows is straightforward, e.g. in energy planning (cf. Section 4.3.2).

4.2.3 Mathematical formulation of the technical flow rate

The quantitative assessment of technical flow rates copes with the main design constraints of well doublets. The addressed issues are *i*) the drawdown in the extraction well, which can lead to the depletion of the aquifer (Section 4.2.3.1); *ii*) the possible return of reinjected water to the extraction well, with the consequence of thermal recycling and decreasing efficiency (Section 4.2.3.2); *iii*) the level increase at the reinjection well, which can result in groundwater flooding (Section 4.2.3.3). The flow rate estimation is based on the characteristics of one entire well doublet including their mutual interference.

4.2.3.1 Maximum drawdown constraint

The estimation of an extractable well yield is fundamental in the quantitative evaluation of groundwater resources (Misstear and Beeson, 2000). The flow rate is generally defined based on a maximum acceptable hydraulic head decline (drawdown) in the well. Considering fully developed wells, a commonly agreed drawdown limit is one third of the saturated aquifer thickness as a technical threshold for sustainable operation (Bezelgues et al., 2010). However, it can also be adjusted in the simulation procedure.

The parameter study was performed with the significant parameters, hydraulic conductivity and aquifer thickness within the ranges shown in Table 4.3. Simulation records from 36 ($6 \cdot 6$, cf. Table 4.3) scenarios were used to fit the constant regression coefficient to 0.195 in equation (4.1).

$$\dot{V}_{drawdown} = 0.195 \cdot K \cdot b^2 \tag{4.1}$$

where:

$\dot{V}_{drawdown}$	$[m^3s^{-1}]$	: lashflow rate at the drawdown threshold b⁄3
		K
$[ms^{-1}]$	$hydraulicconductivity$	:
b	$[m]$	: lashsaturated aquifer thickness

Equation 4.1 calculates the maximum flow rate at the drawdown threshold , in dependence of saturated aquifer thickness and hydraulic conductivity. The maximum extractable flow rate is therefore proportional to the transmissivity and the saturated thickness, which is in line with common approaches such as proposed by Misstear et al. (Misstear et al., 2017). The scatter-plot in Fig. 4.2a displays the fit of the regression estimates compared with the simulation results. In this setting, the maximum flow rate at the drawdown constraint is determined with an influence of the injection well at the limit conditions before a hydraulic breakthrough occurs. Fig. 4.1b displays a cross-section of the hydraulic head through the two wells, where this influence becomes visible. Considering only a single extraction well would result in a larger groundwater decline and therefore in lower pumping rates, as a product of a missing hydraulic support from the injection well (Casasso and Sethi, 2017a). To quantify this influence, the parameter study was repeated with only one extraction well. The results showed the same functional dependency, but consistently 18% lower pumping rates at this drawdown threshold.

4.2.3.2 Hydraulic breakthrough constraint

Apart from a maximum abstraction estimate, additional measures have to be applied to guarantee the sustainable operation of a well doublet. The injection well, located downstream of the extraction well, returns the thermally altered water to the aquifer. Therefore, extensive pumping in the extraction well can result in a hydraulic breakthrough, where the injected water re-enters the extraction well. As a consequence, thermal recycling will eventually occur and the efficiency of the system diminishes (Milnes and Perrochet, 2013). To prevent thermal recycling also for continuous annual loads, the maximum pumping rate without a hydraulic breakthrough is simulated. This leads to conservative flow rate values, where a thermal interaction between the wells is excluded (Lippmann and Tsang, 1980; Clyde and Madabhushi, 1983; Banks, 2009b).

The numerical parameter study to determine the hydraulic breakthrough constraint is also conducted with the model, shown in Fig. 4.1a. The maximised flow rate of a well doublet with no hydraulic feedback is determined by the Darcy velocity vector as it approaches zero in the stagnation point. In the simulation concept, the flow rate of the well doublet changes iteratively, until the Darcy velocity in the middle of the wells is between $\pm$ 0.001 [m/d]. The resulting hydraulic head is displayed in Fig. 4.1b and only pumping rates causing this limit state are considered in the regression analysis.

In the box-model, the significant parameters, hydraulic conductivity, hydraulic gradient and aquifer thickness are varied within the ranges shown in Table 4.3. In addition, the parameter study is extended by a set of five well distances in the range from 10 m to the distance where also a drawdown of ⅓ aquifer thickness is exceeded.

$$\dot{V}_{breakthrough} = \frac{\pi}{1.96} \cdot v_D \cdot b \cdot x_w \tag{4.2}$$

where:

$\dot{V}_{breakthrough}$	$[m^3 s^{-1}]$	: lashflow rate at the hydraulic breakthrough threshold v$_D$
$[ms^{-1}]$	$Darcyvelocity$	:
b	$[m]$	: lashsaturated aquifer thickness x$_w$
$[m]$	$extractiontoinjectionwelldistance$:	

The resulting record of 1080 ($6^3 \cdot 5$, cf. Table 4.3) simulations is used to fit the regression coefficient (1.96) in equation 4.2. Fig. 4.2 b displays the simulation results against the flow rate predictions. With $\dot{V}_{drawdown} = \dot{V}_{breakthrough}$, equation 4.1 and 4.2 can be solved for x_w. As a result, equation 4.3 calculates the maximum well distance for a well doublet operating simultaneously at the drawdown and the breakthrough threshold. Thus, equation 4.3 also calculates the maximum well distance used for the five x_w scenarios.

$$x_w = 0.122 \cdot \frac{b}{i} \tag{4.3}$$

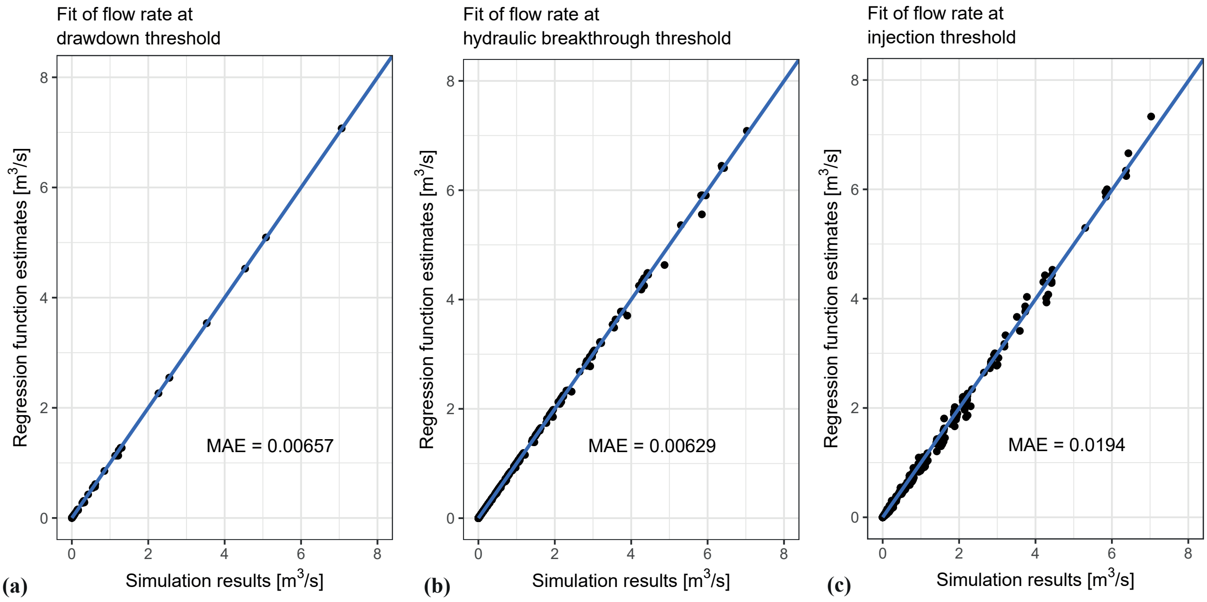

Figure 4.2: Fit of flow rate predictions and Mean Absolute Error (MAE) at hydraulic threshold conditions, shown in Figure 4.1b, for (a) ⅓ drawdown at the extraction well, (b) no hydraulic breakthrough and (c) groundwater rise at the injection well.

where:

b	$[m]$	: lashsaturated aquifer thickness
		x$_w$
$[m]$	$extractiontoinjectionwelldistance$	:
i	$[-]$	: lashhydraulic gradient

4.2.3.3 Injection constraint

In areas where the depth to the groundwater surface is low, the re-injection of water should not cause a rise in the groundwater level, which might result in surface or basement flooding. Therefore, the injection capacity of the aquifer is an important factor in sensitive areas and a sufficient safety margin should be applied (Bouwer, 2002; Casasso and Sethi, 2017a). To prevent flooding problems with a standard well design, an injection limit is included in the assessment of technical flow rate potentials.

For the simulations, the same model is used (cf. Fig. 4.1a). The parameter study of 216 (6^3, cf. Table 4.3) scenarios includes the variation of the hydraulic conductivity, hydraulic gradient and aquifer thickness. The regression coefficients of equation 4.4 (0.789 and 29.9) are fitted, with the record of the induced groundwater level rise at the injection well and the related flow rates. The achieved accuracy of the regression function's predictions is presented in Fig. 4.2c.

Equation 4.4 calculates the flow rate, which can be injected until a rise from the natural to the maximum groundwater level to the maximum allowed level (z_{max}) is reached.

$$\dot{V}_{injection} = (z_{max} - z) \cdot K \cdot b^{0.798} \cdot e^{29.9 \cdot i} \tag{4.4}$$

where:

$\dot{V}_{injection}$	$[m^3 s^{-1}]$	: lashflow rate at the injection threshold
		z_{max}
$[m]$	*maximumallowedgroundwaterlevel*	:
z	$[m]$	: lashnatural groundwater level
		K
$[ms^{-1}]$	*hydraulicconductivity*	:
b	$[m]$	: lashsaturated aquifer thickness
		i
$[-]$	*hydraulicgradient*	:

The scenarios are also simulated with only one infiltration well in order to quantify the hydraulic influence of the extraction well. Because the hydraulic influence of the extraction well diminishes the infiltration cone, the well doublet is able to supply higher pumping rates of around 10% at the same level of groundwater rise.

Finally, the three flow rates ($\dot{V}_{drawdown}$, $\dot{V}_{injection}$, $\dot{V}_{breakthrough}$) are compared. The minimum flow rate is the constraining factor and sets the technical flow rate for a well doublet ($\dot{V}_{tech}$).

4.2.4 Spatial flow rate potential

Based on the ”internal” distance of the well doublet, a suitable ”external” distance to hypothetically neighbouring doublets can be derived with the following results. This step transfers the technical into a spatial potential, because the hydraulic footprint of a well doublet is considered and the water budget in each footprint area is balanced.

The relation between external to internal well distance and the percentage of cycled water in a well doublet (inter-flow) is determined in numerical simulations. For this purpose, a slight modification of the model presented in Fig. 4.1a is used. The area is enlarged to 4000 m edge length to host multiple well doublets, which are lined up perpendicular to the groundwater flow direction in the model centre for 2000 m (cf. Fig. 4.3a). This model setup was constructed with four ”internal” well distances (10, 25, 50, 100 m).

In a sensitivity analysis, external to internal well distance ratios from 1.0 to 3.0 are simulated in 0.2 steps (cf. Fig. 4.3b). The sensitivity is also analysed for different ”internal” well distances and for the influential parameters shown in Table 4.3, summing up to 242 $((6 \cdot 3 + 4) \cdot 11)$

cases. The flow rate ($\dot{V}_{breakthrough}$) for each scenario is calculated from equation 4.2 and it is kept constant for a variation of the external well distances.

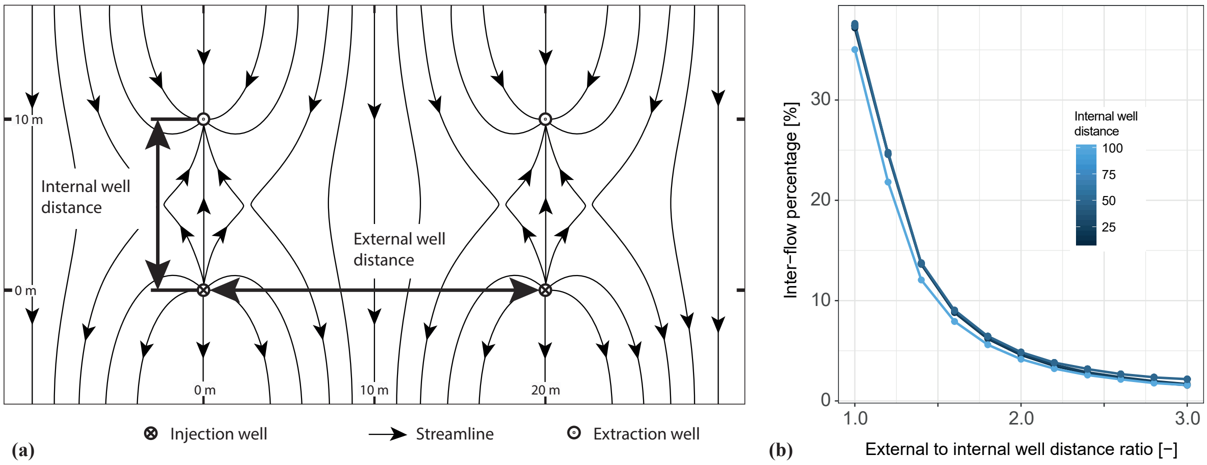

Figure 4.3: (a) Flow field at a 20 m lateral spacing of well doublets with 10 m internal distance. (b) Dependence of external to internal well distance ratio against percentage of inter-flow.

The closer the well doublets are spaced, the more water is circulated between injection and extraction well, because the width of upstream capture zones and downstream release fronts is narrowed. Fig. 4.3b shows the resulting inter-flow percentages for the ratio range of the sensitivity analysis. Since $\dot{V}_{breakthrough}$ is proportional to the respective parametrisation, it can be observed that the remaining influence on the inter-flow is caused only by the ratio of well distances. In consequence, a ratio can be defined, depending on the required conservativeness of spatial estimates. The ratio can further be used to calculate the cell size of the doublet's hydraulic footprint from a certain internal well distance. Fig. 4.3a displays the resulting flow pattern for the hydraulic footprint at an internal well distance of 10 m at a 20 m resolution. This corresponds to a well distance ratio of 2.0 and would limit the inter-flow to moderate values from 4.2 to 4.9% at maximum spacing density.

4.3 The case study: Munich

The proposed TAP method is applied in Munich and enables the city's urban energy planners and decisional authorities to consider the potential of thermal groundwater use.

4.3.1 Hydrogeological setting

The city of Munich is located on the so-called Munich gravel plain. Since the Pleistocene period, fluvio-glacial and fluvial sediments have accumulated on a Tertiary palaeo-surface and built a widespread alluvial plain. A large unconfined groundwater body lies in the Quaternary and Holocene sandy gravels, where the average hydraulic conductivity is $5 \cdot 10^{-3} m/s$. The underlying Upper Freshwater Molasse as topmost Tertiary formation consists of heterogeneously changing layers of predominantly fine sand, silt and clay. Therefore, the Tertiary sediments have a hydraulic conductivity mostly below $1 \cdot 10^{-6} m/s$ and the Tertiary palaeo-surface normally acts as the shallow aquifer bottom (Kerl et al., 2012). Due to channel structures carved into the Tertiary deposits by the former drainage system, the saturated groundwater thickness varies largely in the city area (Bauer et al., 2005). In consequence, a robust spatial interpolation of the aquifer thickness requires a very detailed spatial knowledge of the Quaternary/Tertiary boundary and the groundwater table.

To acquire this information, over 48,000 measurement points from borehole logs and outcrop observations have been reviewed and checked for plausibility in the GEothermal POtential (GEPO) project from 2012 to 2015 (Zosseder et al., 2015). With this data basis the Quaternary/Tertiary boundary was interpolated throughout the hole Munich gravel plain. In addition, an elaborate measurement campaign containing over 6,000 groundwater wells was carried out in April 2014. Fig. 4.4 (top) displays the saturated thickness of Quaternary groundwater. Two major channel structures in North-South orientation can be observed, from Sendling-Westpark (21) to Moosach (23) and from Pasing-Obermenzing (07) to Allach-Untermenzing (10). Here the aquifer thickness is constantly above 10 m, whereas areas with no groundwater indicate that the Tertiary surface is elevated above the surrounding groundwater level. This is the case along the Isar and at some Tertiary hills, such as the ”Aubinger Lohe” (22), which are elevated above ground as inliers. In consequence, the aquifer thickness varies largely and the potential for thermal use of groundwater is very heterogeneous. The potential is also influenced by the distribution of depth to water, which drives the economic accessibility of the resource or may hinder a sustainable groundwater re-injection. The depth to water increases towards the south and is very low in the northern districts of Bogenhausen (13), Feldmoching-Hasenbergl (24) and Aubing-Lochhausen-Langwied (22) (cf. Fig. 4.4 bottom). Furthermore, the aquifer is already intensively used from over 2,600 users in 2017. This situation highlights the need for a spatial potential assessment, before an integration of the resource in energy planning can be elaborated.

4.3.2 Assessment of the thermal groundwater potential with the TAP method

As presented in Section 4.2.1, the first assessment step is the consideration of legislative and operational constraints valid for Munich. Initially, the maximum approvable drilling depth, i.e. the Quaternary/Tertiary layer boundary, and the drinking water protection areas are reviewed. In the next step, the maximum flow rate values area calculated according to the constrains for drawdown, injection and hydraulic breakthrough (cf. Section 4.2.3).

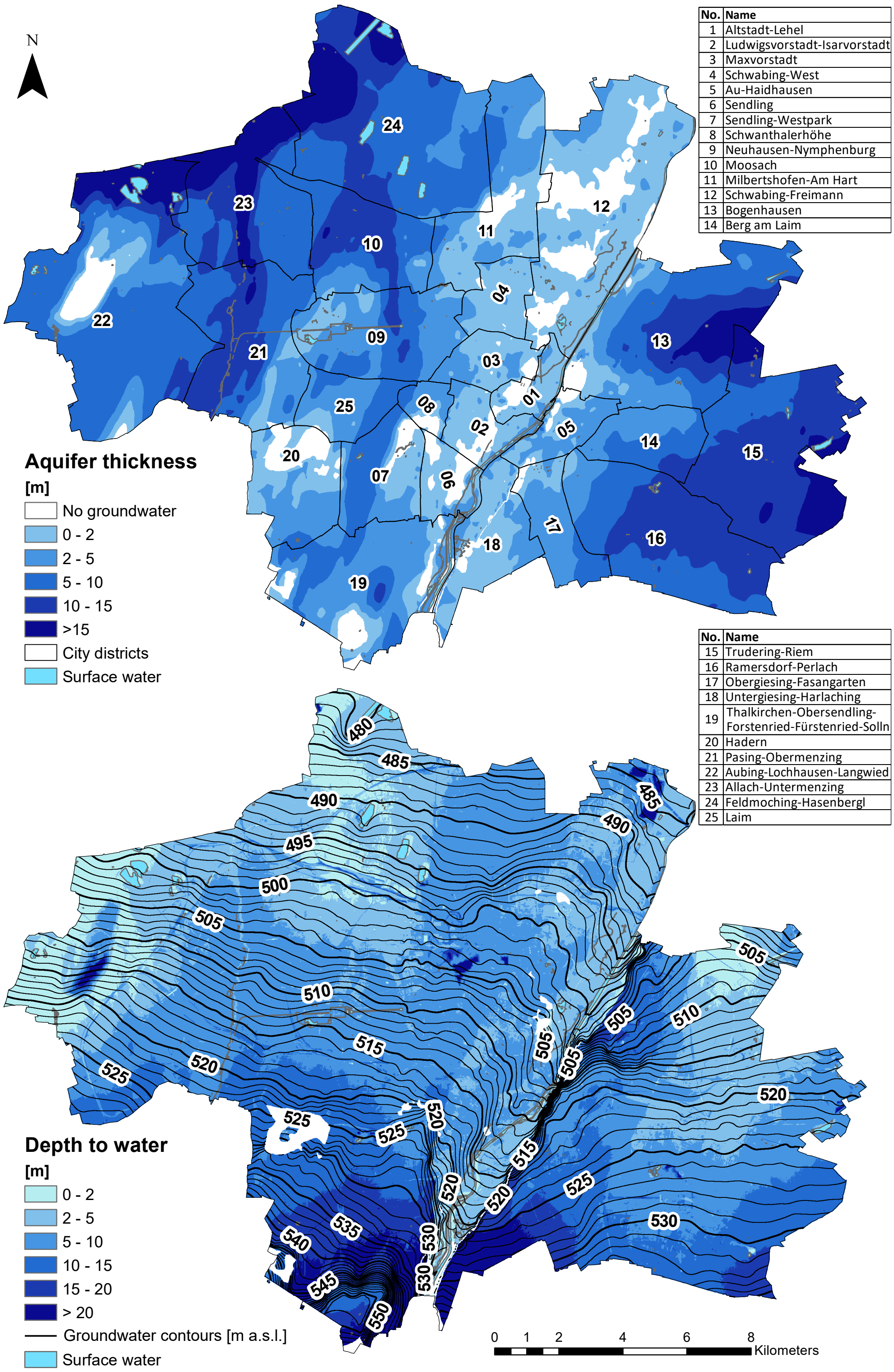

Figure 4.4: (top) Saturated thickness of the quaternary groundwater and city districts of Munich. (bottom) Depth to groundwater-table with groundwater contour lines.

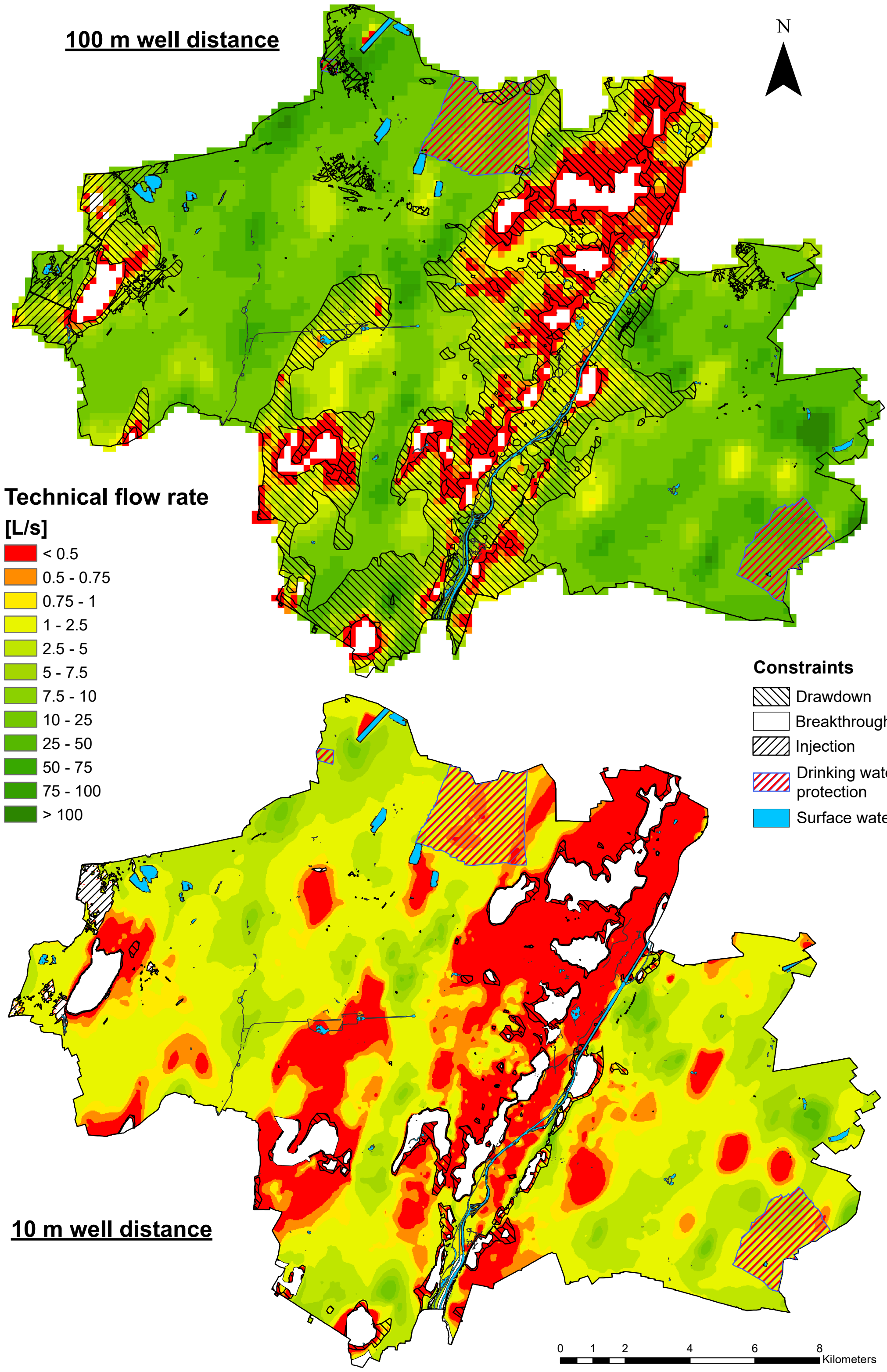

Figure 4.5: Technical flow rate with spatial constraints for 100 m well distance in 200 m resolution (top) and 10 m well distance in 20 m resolution (bottom).

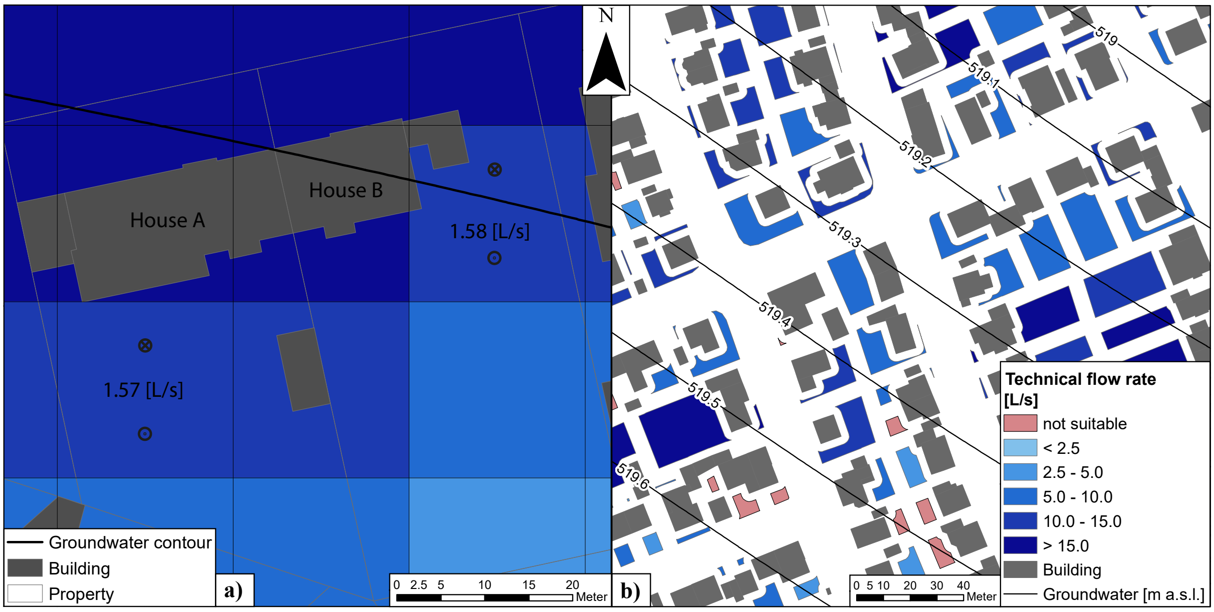

Figure 4.6: (a) Application example of the raster-cell technical flow rate assessment. (b) Application example of a plot-wise technical flow rate assessment.

Fig. 4.5 shows the resulting technical flow rates for well distances of 100 m (top) and 10 m (bottom). The resolution of the potential maps is set to 200 m and 20 m respectively, to consider the hydraulic footprint of the well doublets. As presented in Fig. 4.3b, this limits the interflow, i.e. the share of circulated water in a doublet, to below 5%, if systems in all neighbouring raster cells would be realised. Two different kinds of hatching indicate the areas where the constraint on groundwater drawdown (up to one third of the saturated aquifer thickness) or rise (up to 0.5 m below ground surface) applies. However, for both well distances the hydraulic breakthrough is the prevailing limiting factor in most of the area. Only in Schwabing-Freimann (area no. 12 in Fig. 4.4 top) and around the river Isar, the drawdown constraint is stronger than the one on hydraulic breakthrough, due to the low aquifer thickness. The injection limits the potential flow rate only in the north-western part such as Aubing-Lochhausen-Langwied (area no. 22 in Fig. 4.4 top), where the depth to water table can already be smaller than the safety threshold of 0.5 m. Increasing the well distance to 100 m leads to a ten-fold increase of the related flow rate ($\dot{V}_{breakthrough}$), thus amplifying the effect of the other constrains. The drawdown becomes the limiting factor in larger areas of low saturated aquifer thickness west of the Isar and in areas of a low hydraulic gradient (cf. Fig. 4.4 top). With an elevated $\dot{V}_{breakthrough}$ limit, also the injection constraint is active in a larger area of low depth's to water, especially in Aubing-Lochhausen-Langwied (22).

Fig. 4.6 a shows an exemplary application of the raster map in Fig. 4.5 (bottom) with two hypothetical well doublet installations. The two buildings (A and B) and their related properties occupy distinct raster cells of $20 \times 20m$ resolution. As the potential is calculated with a fixed doublet distance of 10 m, a rather low potential flow rate (1.58 L/s) is resulting, which would allow the installation of a GWHP with a power of $44kW$ in the hypothesis of applying a temperature difference of $\Delta T = 5K$ and a $COP = 4$. However, on the properties of these two houses well distances larger than 10 m could be accommodated, although they are way below 100 m, i.e. the other hypothetical well distance considered in Fig. 4.5 (top). The flexibility of TAP also allows to calculate the open-loop geothermal potential of every single plot of land, considering the best practice of installing extraction and injection wells aligned with the groundwater flow. Fig. 4.6 b shows an example of this plot-wise assessment, with the available space for a well doublet. Buffer distances provided by regulations are included, such as the 3 m minimum distance from neighbouring plots or buildings prescribed in Bavaria (Bayerisches Landesamt für Umwelt, 2012). Plots are marked in red if the minimum prescribed well distance of 10 m is not feasible. With the plot-wise approach, the TAP method meets all requirements for an application in spatial energy planning on the building scale. Since only one plot with one well doublet is considered at a time, the flow rate results cannot be aggregated as mutual hydraulic and thermal interferences are not taken into account. If the required well distance cannot be installed, a comparative evaluation of the three constrained flow rates can indicate the feasibility of a specific thermal short circuit analysis.

4.3.3 Comparison of TAP results with existing installations

In Bavaria, shallow geothermal applications with an approved annual extraction of more than 100,000 m^3 have to report the monthly extracted volumes to the approving authority. Hence, the maximum monthly flow rates in 2015 are compared to the technical flow rate estimates with a validation data set of 97 well doublets. Flow rates are calculated for the drawdown limit from equation 4.1 and the hydraulic breakthrough limit from equation 4.2. The values of relevant hydrogeological parameters are averaged within a circle around the wells. The radius of the circle

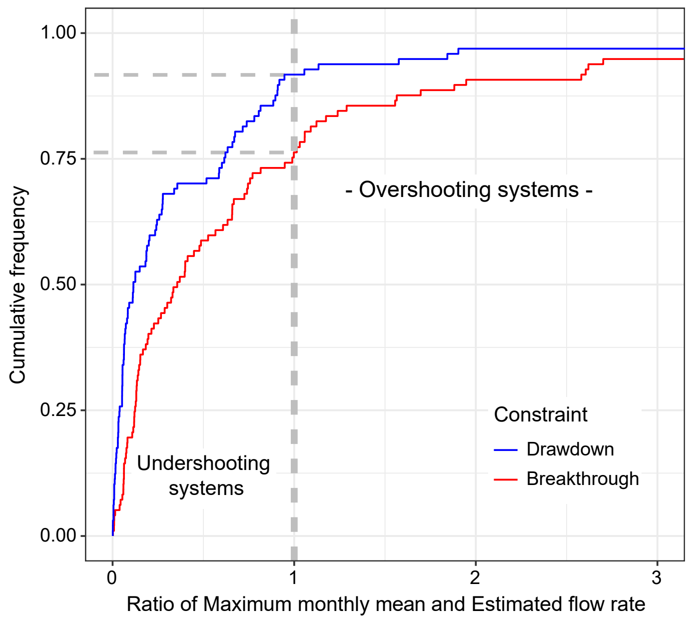

Figure 4.7: Empirical cumulative distribution of the observation/estimation ratio for drawdown and hydraulic breakthrough limits.

is calculated with respect to the re-
ported pumping rates after Todd and Mays (2005). In addition, the well doublets are considered to be parallel to the regional groundwater flow and horizontal filter wells are excluded. Fig. 4.7 shows the cumulative distribution of the over- and undershooting systems compared to the estimates. The abscissa shows the ratio of maximum monthly means and estimated flow rates, thus systems with a value higher than one extract more than expected. 10 % of the reported extractions exceed the estimated flow rate at the drawdown limit and 26 % overshoot the rate at the hydraulic breakthrough limit (cf. dashed lines in Fig. 4.7).

Two characteristics of the monitoring data should be highlighted. Although only large systems have been evaluated, they do not necessarily use the maximum potential at their site. Additionally, the full-load operation time of the peak month is not known. Apart from that, thermal recycling will need a certain duration of excessive pumping to develop. Especially for the examined doublets with a mean distance of 140 m. In consequence, mean values are more appropriate to evaluate a breakthrough risk than short full-load extractions.

From Fig. 4.7, we can observe that the majority of systems do not exceed the established drawdown and hydraulic breakthrough limits. No severe overshooting is present and at five well doublets, which exceed the estimated hydraulic breakthrough threshold by 1.8 to 2.6 times, negative influences of thermal recycling have already been reported. However, the reported issues are not severe enough to endanger a sustainable operation, which indicates the conservative character of the hydraulic breakthrough constraint. This conservative character is also visible in the comparison of the constraints, where the breakthrough limit derives lower flow rates than the drawdown limit. Some of the systems could also be deliberately designed with a hydraulic support to cover the demand and thermal recycling is tolerated to a minor extent. In summary, it can be stated that the technical flow rates have proven their suitability as a conservative peak extraction estimate.

4.4 Discussion

The presented method offers a workflow to assess a quantitative potential for the thermal use of groundwater. It integrates the relevant regulatory and operational constraints for a sustainable operation of well doublets with a consideration of their hydraulic impact. Thus, spatial inquiries of technologically achievable flow rates are possible. The necessary functional relations are derived through non-linear regression analyses of numerical simulation results, as reported in Section 4.2.3. The defined hydraulic constraints assume a continuous plant operation, which provides a conservative potential estimation.

The derived approach can be applied in spatial energy planning at the building scale and provides a basis to compare the resource with other renewable options. Further, the assessed potentials can be used for thermal groundwater management, enabling authorities to adapt approval procedures and rise the awareness for this heating and cooling option early in the planning process.

Specific constraints for a sustainable flow rate estimation in open-loop systems have been introduced in previous potential assessment studies (cf. Table 4.1). Drawdown limits dependent on aquifer thickness are generally used to estimate reliable well yields, with fractions from 25 % to 70 % of the saturated thickness (García-Gil et al., 2015a; Misstear and Beeson, 2000). In this paper, we provide formulae valid for a drawdown threshold of ⅓ of the saturated thickness, as prescribed in Munich and recommended in France (Bezelgues et al., 2010). However, considering only a linear correlation between flow rate and drawdown does not include all technologically constraining factors. Casasso and Sethi (2017a) included an additional re-injection limit to avoid flooding with a safety distance to the surface of 3 m by using the Cooper-Jacob equation (Jacob, 1946). With the presented equation 4.4, this threshold is adaptable and can be set according to local requirements, as done in Munich with a value of 0.5 m. In addition, the TAP method considers the mutual hydraulic effect of abstraction and reinjection in numerical simulations, which provides specific adaptations for well doublets.

Further, the flow rate of a well doublet is constraint to prevent a hydraulic breakthrough. Only the breakthrough constraint allows a utilization of the potential values for spatial energy planning, because it includes the internal well distance as a spatial influence on the hydraulically affected zone. Since the propagation of thermal anomalies is retarded by a factor of 2 to 3, the hydraulic breakthrough occurs before the thermal breakthrough (Shook, 2001). Therefore, it serves as a feasible and conservative threshold to eliminate the risk of thermal recycling Galgaro and Cultrera (2013); Casasso and Sethi (2015); Banks (2009b). For the calculation of a hydraulic breakthrough, authors commonly refer to an analytical solution by Lippmann and Tsang (1980) and Clyde and Madabhushi (1983), which is derived from the same simplifying assumptions and leads to comparable results. Möderl et al. (2010) derived well spacing formulae for doublets in horizontal and vertical direction. The study also fitted results of parameter variations in numerical simulations to an empirical equation by solving a not further documented minimisation problem. However, the aquifer thickness was not treated as independent parameter and a combination of 5 % injected water which return to the abstraction well as inter-flow and 0.5 K of thermal recycling was chosen as acceptable breakthrough criteria for flow rates up to 1 L/s. Although the results are not directly comparable, the well distances by Möderl et al. are significantly lower then the results from equation 4.2, especially for higher flow rates, which confirms the conservativeness of the approach.

Analytical solutions for an optimised external well spacing perpendicular to the groundwater flow are proposed by Javandel and Tsang (1986) for groundwater treatment. The derived formulae calculate well spacings that prevent flow to pass between the pumping wells, neglecting an interference between injection wells. Javandel & Tsang did not integrate an influence of the wells on the drawdown. Also the study of Clyde and Madabhushi (1983) gives only qualitative information on an external well spacing. The objective of our study was to derive the footprint area of hydraulically sustainable well doublets with a balanced water budget. Therefore, the use of numerical models provided a specific solution, which allows spatial queries.

Assumptions and Limitations

The presented method assumes several commonly used simplifications (García-Gil et al., 2015a; Groupe de travail PDGN, 2010; Casasso and Sethi, 2017a). Since idealised 2D box-models are used for the simulations, the methodology is only suitable for porous aquifers with a certain hydrogeological homogeneity and the method is designed for unconfined conditions, which are more frequent in shallow aquifers. Further, the TAP-method should only be applied within the varied parameter ranges, which however are very wide as shown in Table 4.3, and in the absence of complex boundary conditions, e.g. recharge from surface water bodies. In the procedure, the hydrogeological parameters are averaged in the assessed area, i.e. the hydraulic footprint or the plot extent. Thus, the error introduced through averaging may increase for larger well distances in heterogeneous conditions. In addition, all flow rate relations are studied in steady-state simulations with fully penetrating wells. This is intended to gain results with general validity, because the estimates represent a constant operation of the open-loops system. However, domestic heating and cooling loads, as well as injection temperatures are typically very variable. In consequence, the potential assessment serves as a conservative initial measure, but can not substitute demand specific designs for abstraction or injection, like the use of horizontal filter wells or infiltration ditches. This is also the case for installations where the injection well can not be built directly down-gradient or the extraction occurs at a different elevation from the injection.

In a future perspective, a consideration of thermal anomalies can lead to a spatial assessment of thermal potential, without negative interaction of installations. Additionally, an inclusion of dynamic hydraulic and thermal processes would reveal synergetic effects between installations or enable users to test the influence of different demand scenarios. At a certain point however, a method designed for application in a GIS-workflow can not cope with a site-specific numerical model, which comprehensively considers the effect of significant influences in transient simulations.

4.5 Conclusion

This paper proposes a method to assess the spatial extraction potential for thermal use of groundwater within the relevant operational and regulatory limits. The technical flow rate potential between extraction and injection well is estimated by three hydraulic constraints. The constraints ensure that the drawdown in the extraction well does not exceed a specific limit, that the groundwater table in the injection well does not rise above a specific limit, and that the flow rate does not lead to a hydraulic breakthrough in the well doublet. Additionally, the mutual hydraulic interference of well doublets is calculated to derive a feasible spatial density without inducing a significant cycling of water between the wells.

Finally, the potential assessment was performed in Munich. Since areas with a low aquifer thickness or depth to water are present, the technical flow rate assessment displays the importance of each constraint. A comparison of technical flow rate estimates with monthly groundwater extractions from large open-loop systems showed the suitability of the estimates as conservative peak extraction values. Specifically, the TAP-method delivers quantitative potential values, which are based on a highly transferable and adaptable numerical approach. The method is thus well-suited to serve as a tool for the integration of thermal groundwater use in future energy strategies not only in Munich but in similar environments worldwide.

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Chapter 5

City-scale solutions for the energy use of shallow urban subsurface resources – Bridging the gap between theoretical and technical potentials

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Abstract

One solution for reducing the current consumption of fossil fuels is a more frequent use of shallow geothermal energy. However, particularly regarding urban subsurface resources, increased use conflicts are predictable. Consequently, reasonable exploitation of subsurface resources requires an assessment of technologically achievable energy potentials with scientific based tools. We present application-oriented management tools which target on deriving shallow subsurface energy potentials. 3D groundwater flow and heat-transport models are used to capture groundwater flow and heat transport dynamics on the city- and quarter-scale, 2D box models are used to quantify technically feasible extraction rates of well doublets for groundwater heat pump systems.

For Basel (Switzerland), prospective large theoretical energy potentials can be derived for areas with high advective heat flux and high temperature gradients. Likewise, single city quarters are suitable for 'active' thermal use with well doublets, whereas thermal power potentials reach 1.2MW. Regarding 'passive' installations of energy absorbers in subsurface structures located within the groundwater, energy potentials amount to 4 and up to 40Wm^{-2}.

The assessment results can be integrated into urban energy plans and support architects, city planners and potential users to acquire initial site-specific information on the technical feasibility of shallow geothermal energy systems.

Glossary

A_{heat}	serviceable surface to be heated [m^2]
$ATES$	Aquifer Thermal Energy System
BHE	Borehole Heat Exchanger
COP	Coefficient of Performance
C_w	specific heat capacity of water as the product of specific heat [$4.20 \cdot 10^6 kJkg^{-1}K^{-1}$] and the density of water at 10°C [$999.7 kgm^{-3}$]
E_{adv}	advective energy transport by groundwater flow, corresponds to a heat flux per unit area, advective heat flux density [Wm^{-2}]
E_D	Energy Demand for heating [$kWhm^{-2}a^{-1}$]
E_{fluid}	Energy stored in groundwater „fluid phase“ [J]
E_{pot}	Energy potential [$MWha^{-1}$]
E_{SCOP}	technical Energy potential [$MWha^{-1}$]
E_{solid}	Energy stored in the matrix „solid phase“ [J]
E_{tech}	technical thermal potential [kW]
E_{therm}	thermal Energy potential [$MWha^{-1}$]
E_{total}	total subsurface Energy content [J]
GW_{depth}	depth to GroundWater [m]
$GW_{thickness}$	GroundWater thickness [m]
GWB	GroundWater Body
$GWHP$	GroundWater Heat Pump
i	hydraulic gradient [%] and [-]
k_f	hydraulic conductivity [m s-1]
P_{therm}	thermal Power potential [kW]
Q	City Quarter [#]
$Q_{breakthrough}$	well operation constrained by prevention of a hydraulic breakthrough [m^3s^{-1}]
$Q_{drawdown}$	extraction constrained by tolerable drawdown in the extraction well [m^3s^{-1}]
$Q_{injection}$	injection constrained by tolerable water level rise in the injection well [m^3s^{-1}]
Q_{tech}	technical hydraulic potential [Ls^{-1}], [m^3s^{-1}]
$S - GW_{depth}$	depth of Subsurface structure to GroundWater
$SCOP$	Seasonal Coefficient Of Performance
sd	standard deviation
SGE	Shallow Geothermal Energy
$SUHI$	Subsurface Urban Heat Island
TAP	Thermal Aquifer Potential
T_{cal}	Calculated Temperature [°C]
TGW	GroundWater Temperature [°C]
T_{Nat}	Natural groundwater Temperature [°C]
T_{Ref}	Reference Temperature [°C]
UHI	Urban Heat Island
$UR_{thickness}$	thickness Unconsolidated Rock deposits [m]
v_{Darcy}	Darcy groundwater flow velocity [ms^{-1}]
V_{fluid}	effective groundwater Volumes [m^3]
x_w	Well distance [m]
ΔT	Temperature spread [K]
$3D - THM$	3D Thermal Hydraulic Model
$2D - BM$	2D Box Models

5.1 Introduction

The 2030 climate and energy framework of the European Union (EU) defines three targets: at least 40% reduction of greenhouse gas emissions, at least 32% share of renewable energy, and at least 32.5% improvement in energy efficiency for the year 2030. In November 2018, the EU presented a long-term strategy leading to a climate-neutral economy by 2050 in order to keep the global temperature increase below 2°C (EC, 2018). Apart from defining ambitious goals, the solutions for achieving them are yet to be elaborated.

Currently, energy planning concepts and SECAP's as an EU-wide instrument are developed for many cities. This includes the evaluation and advancement of alternative energy sources which allow reducing the current use of fossil fuels. Particularly in urban environments, the increased use of shallow geothermal energy for 'cooling' purposes and the diffuse thermal impact of anthropogenic subsurface structures lead to elevated ground temperatures. This 'waste heat' could represent a sustainable energy source for heating purposes.

In the heating and cooling sector, a considerable alternative to fossil fuel is the utilization of shallow geothermal energy (SGE). At present, the possibilities to use SGE for heating and cooling are progressively developing into a broad variety of small- and large-scale applications (David et al., 2017). Nevertheless, a greater awareness of SGE among politicians and technicians has to be realized (Schiel et al., 2016). Potential assessments can provide the necessary information to raise awareness. Particularly, quantitative assessments allow an integration of SGE in urban energy planning and enable a comparative evaluation with other renewable resources.

Thermal groundwater regimes in urban areas are affected by numerous anthropogenic influences, such as the urban heat island effect (UHI), surface sealing, subsurface infrastructure, as well as the use of groundwater as an efficient cooling medium. The diffuse heat input propagates into the shallow ground and leads to the so-called 'subsurface urban heat island' effect (SUHI) which is already observed in many urban areas, like in Winnipeg, Canada (Ferguson and Woodbury, 2007); Cologne (Zhu et al., 2011); Berlin, Munich, Frankfurt, Karlsruhe and Darmstadt (Menberg et al., 2013a), Germany. An increased use of SGE for heating could counteract the present thermal imbalance of the urban subsurface. However, in Munich, Germany, for example, cooling with groundwater already accounts for two third of the installed capacity. Due to innovations in insulation materials and global warming, the heating demand of buildings will continuously decrease, whereas the demand for cooling will increase (Herbert et al., 2013). Likewise, efficiently insulated buildings are characterized by lower required system temperatures. All mentioned developments are favourable for choosing SGE enhanced with a heat pump or for free-cooling. Potential assessments offer the possibility to highlight the resulting efficiency gains for heating with SGE and thereby support balancing the subsurface heat budget and reducing the SUHI effect.

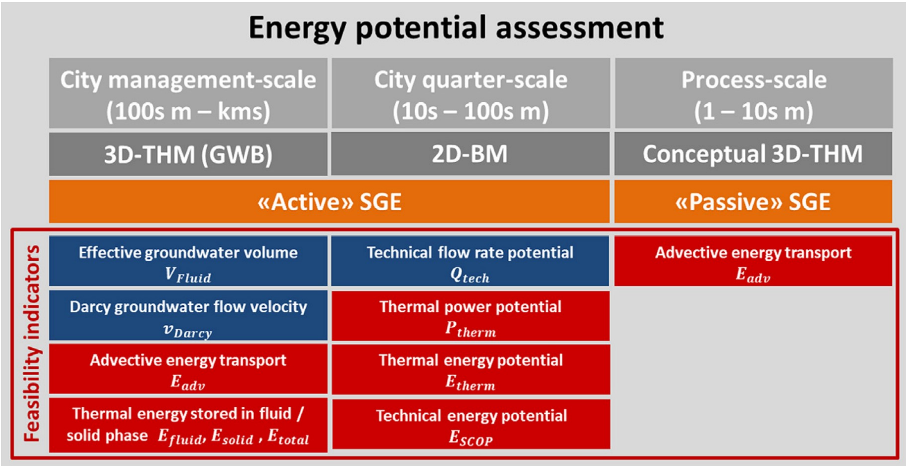

Figure 5.1: Conceptual approach and feasibility indicators for the scale-dependent energy potential assessment of shallow urban subsurface resources by means of different modelling approaches for 'active' and 'passive' SGE solutions.

Especially at the complex urban scale, only numerical flow and heat-transport modelling is able to offer resilient predictions for a sustainable management of subsurface thermal resources. It is generally accepted that a more detailed knowledge of the highly transient spatio-temporal behaviour of hydraulic and thermal groundwater regimes as well as the interaction of different geothermal usages is still needed to better understand the SUHI effect, e.g. Huggenberger and Epting (Huggenberger and Epting, 2011).

However, so far, only a few studies have approached resource management and the exploitation of ground source energy at the scale of urban aquifers (e.g. London, United Kingdom (Herbert et al., 2013); Basel, Switzerland (Mueller et al., 2018), Barcelona, Spain (Alcaraz et al., 2016b, 2017), Zurich, Switzerland (Rivera et al., 2017a), Pisa, Italy (Sbrana et al., 2018)). In Ref. Miglani et al. (2018) a methodology to calculate long-term shallow geothermal energy potential for an urban neighbourhood is presented. However, the study focuses on borehole heat exchangers (BHE) which continuously extract heat over long periods and only result in 'cooling' of the ground. Likewise, most studies do not account for advective heat-transport related to thermal groundwater use, which is the most important heat-transport process for the spatial (re)distribution of energy in the subsurface, especially in unconsolidated, highly permeable sediments, e.g. Russo and Taddia (2010), Epting et al. (2018a) and Epting et al. (2018b). In Bayer et al. (2019), previous work for quantifying the low-temperature geothermal potential in the urban subsurface and groundwater is reviewed based on different definitions of the geothermal potential and different assessment methods are compared.

Evaluations in densely urbanized areas of Basel (Switzerland) show that groundwater is warmed up 16-18°C, whereas the natural groundwater temperature corresponds to the average annual air temperature of about 10°C (Epting and Huggenberger, 2013). The current thermal state of Basel is a result of different natural and anthropogenic influences and their mutual spatiotemporal interaction (Mueller et al., 2018; Epting et al., 2017a). Previous studies have shown that further SGE systems only for ‘cooling’ purposes are not advisable for the investigated groundwater resources (Epting et al., 2013). On the other hand, a thermal use of the suburban ‘waste heat’ is promising. Epting et al. (2018a) assessed the heat-potential of the urban groundwater resources in Basel and subsequently relate it to the heat-demand (Epting et al., 2018b). The following approach is a first step of how to optimize the management of thermal resources in the urban subsurface. In addition, we estimate a possible increase in the share of renewable energy sources by using only the “waste heat” stored in urban groundwater.

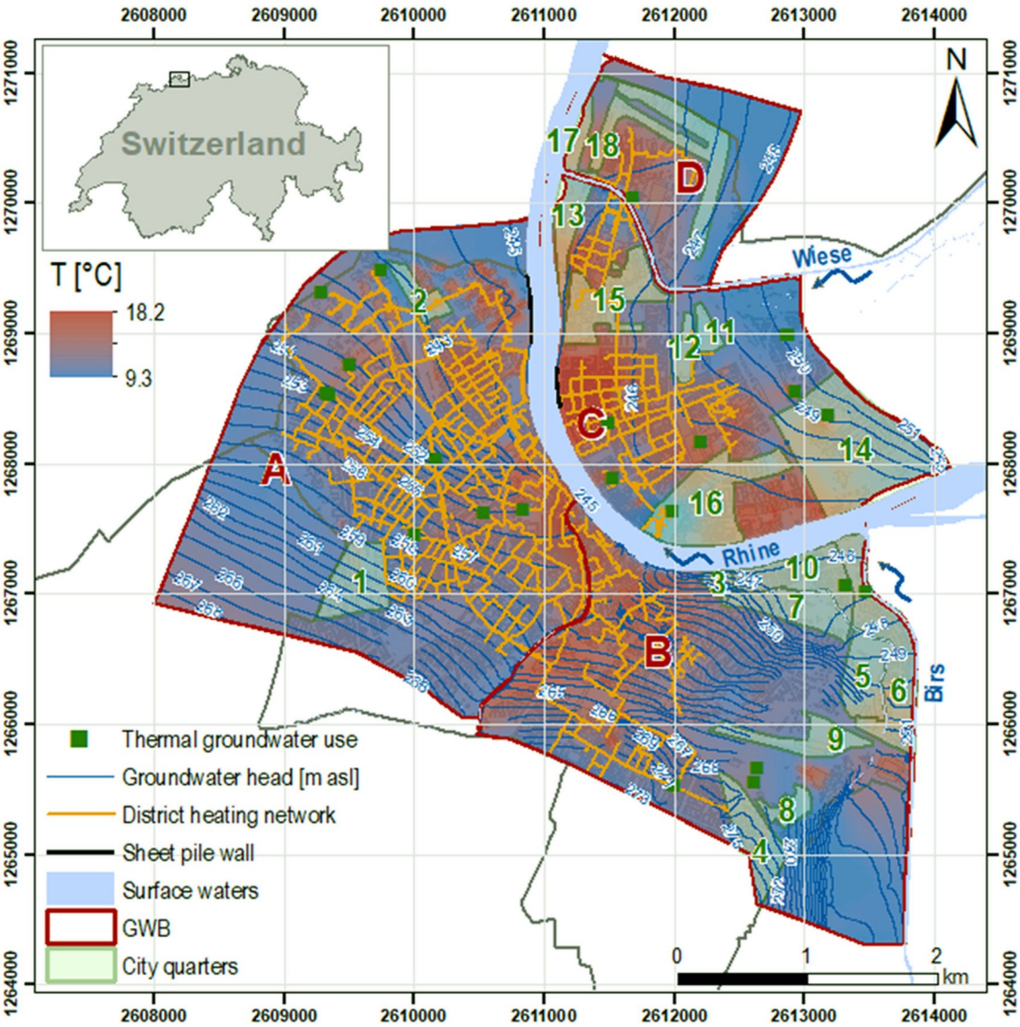

Figure 5.2: Urban GWBs (A-D), selection of city quarters (Q1-18) and parts of the district heating network in Basel, Switzerland. Mean simulated groundwater temperatures and hydrogeological regime for the years 2010-2015 (modified after Mueller et al. (2018)).

Table 5.1: Characteristics of the different city quarters.

GWB	Quarter [Q]	Area [ha]	$UR^a_{thickness}$ [m]	$GW^a_{thickness}$ [m]	GW^a_{depth} [m]	k^a_f [$10^{-3}ms^{-1}$]	T^a_{GW} [°C]
A	①	23.4	18.9	4.2	14.7	1.5	13.8
	②	9.0	22.2	9.7	12.4	1.8	14.3
B	③	4.5	9.1	1.7	7.0	1.5	14.6
	④	25.4	12.1	0.6	11.9	1.0	13.8
	⑤	19.9	15.6	2.2	14.4	1.1	13.9
	⑥	42.5	9.6	4.2	5.9	0.8	14.5
	⑦	20.1	20.7	2.5	18.2	4.4	13.9
	⑧	6.9	11.1	0.02	12.2	2.9	12.8
	⑨	16.8	13.4	0.3	14.0	3.0	13.6
	⑩	25.6	13.5	4.8	8.5	2.1	14.1
C	⑪	5.3	18.9	11.5	7.5	3.5	12.7
	⑫	7.0	17.5	9.2	8.4	2.8	13.3
	⑬	14.4	11.0	7.7	3.1	1.9	14.8
	⑭	80.7	21.0	8.8	12.3	3.9	14.0
	⑮	29.8	13.9	7.7	6.0	8.7	15.0
	⑯	43.0	15.5	5.8	10.5	1.1	14.1
D	⑰	35.9	12.7	7.3	5.4	4.0	13.4
	⑱	7.4	8.6	6.9	2.3	2.2	15.0

[a] Mean of the district

This contribution derives energy potential measures of the shallow urban subsurface by means of numerical high-resolution 3D groundwater flow and heat-transport models (3D-THM) as well as 2D box models (2D-BM). The 3D-THMs are used to investigate the spatio-temporal development of groundwater abundance and advective energy transport on the city-scale and for 18 selected city quarters. Moreover, local city-specific factors, i.e. impacts of possible new installations on nearby contaminated sites or existing uses of the subsurface and the groundwater, are discussed for the different evaluated city quarters. Additionally, the 2D-BMs are used to quantify feasible extraction rates of well doublets (groundwater heat pumps GWHPs) and the resulting hydraulically influenced area for the selected 18 city quarters. The joint evaluation of the two numerical modelling approaches allows bridging the theoretical assessment of city-scale energy potentials with the technical approach for the implementation of GWHPs on the scale of city quarters.

To complement the potential evaluation of SGE, technical solutions for 'active' (GWHPs) and 'passive' (energy absorbers within building envelopes) geothermal applications are investigated for representative hydraulic and constructional settings in the city of Basel. Particularly developed feasibility indicators, which are related to the abundance of groundwater and the stored thermal energy, allow judging the potential for the realization of different geothermal applications in the various city quarters. Finally, possible impacts related to potentially contaminated sites as well as existing subsurface and groundwater use located within the vicinity of possible new installations are discussed for the different city quarters.

5.1.1 Conceptual approach

Fig. 5.1 illustrates the followed conceptual approach. For the thermal management of urban subsurface resources at the city-scale and at the scale of city quarters different modelling approaches have been followed to study 'active' and 'passive' SGE solutions. The SGE solutions are judged by feasibility indicators which allow a comparison of the potential for different areas of the investigated groundwater bodies (GWB), the studied city quarters (Q) as well as the studied 'active' and 'passive' SGE solutions.

Table 5.2: SGE systems and numerical realization.

Active: Open loop systems	**Numerical realization**
GWHP Extraction of groundwater and reinjection of thermally used water into the aquifer	• Flow rates and temperatures for different city quarters based on 3D-THM • "Technical potential": hydraulic (groundwater abundance) and subsurface energy potential under consideration of specific boundary conditions (e.g. well spacing, Δ T) with numerical 2D-BM (grid cell resolution) • Simulation of withdrawal and rejection wells (well doublets) • Calculation of groundwater and energy yields ($v_{Darcy}, \Delta T, E_{adv}, Q_{tech}, E_{tech}$)
Passive Energy absorbers (e.g. diaphragm walls)	
Building envelopes of subsurface structures for heat exchange	• Integration into conceptual 3D-THM • Parameter/sensitivity analysis of representative hydraulic and structural settings

5.1.2 Approaching the city- and quarter-scale

For the present study, an approach on the city- and quarter-scale was chosen. Since the results are designed to offer information for the integration into and supplementation of energy supply networks as part of the regenerative energy mix in urban areas, large-scale potential assessments are more appropriate compared to focusing only on individual houses (Epting et al., 2013; De Carli et al., 2014). 18 city quarters are chosen on the following selection criteria (Fig. 5.2): (A) current or foreseen urban development and (B) at present no connection to the existing district heating network. Table 5.1 summarizes the geometric settings and mean hydrogeological parameters derived from the 3D-THMs for the time period 2010 to 2015 (Mueller et al., 2018).

5.1.3 'Active' & 'passive' SGE solutions

Table 5.2 summarizes SGE system types and elucidates their numerical realization. By means of 'active' SGE solutions, like GWHPs, groundwater is withdrawn and reinjected from the saturated zone through well doublets, 'passive' SGE solutions involve thermoactive ground structures (e.g. energy piles, diaphragm walls, concrete slabs) which extract energy conductively through embedded pipe loops (Laloui and Di Donna, 2013; Brandl, 2006). Real-world applications were realized by pilot studies, and some of them also were part of large infrastructure projects, including energy geocomposites for tunnels (Brandl et al., 2006). Several practical applications of this technology are already operational, particularly in some countries such as Austria (Adam, 2009), Germany (Brandl, 1998), the United Kingdom (Bourne-Webb et al., 2009), and Switzerland (Pahud, 2013).

5.1.4 Feasibility indicators

Table 5.3 summarizes feasibility indicators derived from the different modelling approaches, including the 3D-THM (city-scale, i.e. GWBs, city quarters and conceptual model evaluations) and the 2D-BM (city quarters). In the following, the chosen indicators are presented in detail.

5.1.5 Effective groundwater volume V_{fluid} and Darcy velocity v_{Darcy}

The knowledge of V_{fluid} together with v_{Darcy} allows estimating the groundwater abundance on the city-scale as well as for the different city quarters. These key parameters can directly be derived from the 3D-THMs.

5.1.6 Advective energy transport E_{adv}

Particularly in highly permeable unconsolidated sediments, the advective heat transport with groundwater flow is the most important heat transport process for the spatial redistribution of energy in the subsurface and can be derived from the 3D-THMs (Epting et al., 2018b,a). E_{adv} corresponds to a heat flux per unit area and can be calculated from the volumetric heat capacity of water C_w, the Darcy groundwater flow velocity v_{Darcy} and the difference between simulated temperatures T_{cal} and a reference temperature T_{Ref} (Stauffer et al., 2014). For T_{Ref} e.g. a natural groundwater temperature (for Basel T_{Nat} amounts to approx. 10°C) or such related to regulations can be chosen. The heat flow densities E_{adv} were calculated for the entire urban area and the 18 selected city quarters.

Table 5.3: Feasibility indicators derived from the two modelling approaches.

	Feasibility indicators	Calculation	
3D-THM	Effective groundwater volume	$V_{Fluid}[m^3]$; model output	
	Darcy velocity	$v_{Darcy}[ms^{-1}]$; model output	
	Advective energy transport	$E_{adv}[kWm^{-2}] = C_w[kJm^{-3}K^{-1}]\ v_{Darcy}[ms^{-1}](T_{cal} - T_{Ref})[K]$	(Eq. 1)
	Thermal energy stored in fluid	$E_{fluid}[J]$; model output	(Eq. 2)
	and solid phase	E_{solid}; model output	(Eq. 3)
		$E_{total}[J] = E_{fluid}[J] + E_{solid}[J]$; model output	
		$E_{fluid}/E_{solid}[-]$	
2D-BM	Technical flow rate potential Q_{tech}	Required parameters: (derived from the mean groundwater levels 2010-2015 from 3D-THM)	
		(1) $GW_{thickness}[m]$	
		(2) $GW_{depth}[m]$	
		(3) $i[-]$: calculated from groundwater contours	
		(4) $k_f[ms^{-1}]$: derived from 3D-THM model calibration	
		(5) Well distance $x_w[m]$: separate evaluation of 10, 20 and 50 m	
		$Q_{drawdown}[m^3s^{-1}] = 0.195 * k_f ms^{-1} GW^2_{thickness}[m^2]$	(Eq. 4)
		$Q_{injection}[m^3s^{-1}] = GW_{depth;max}[m] - GW_{depth}[m]k_f[ms^{-1}]GW^{0.798}_{thickness}[m]e^{29.9i}[-]$	(Eq. 5)
		$Q_{breakthrough}[m^3s^{-1}] = 1.60k_f[ms^{-1}]i[-]GW_{thickness}[m]x_w[m]$	(Eq. 6)
		$Q_{tech}[m^3s^{-1}] = min(Q_{drawdown}[m^3s^{-1}], Q_{injection}[m^3s^{-1}], Q_{breakthrough}[m^3s^{-1}])$	(Eq. 7)
	Thermal power potential	$P_{therm}[kW] = C_w[kJm^{-3}K^{-1}]Q_{tech}[m^3s^{-1}]\Delta T[K]$	(Eq. 8)
	Thermal energy potential	$E_{therm}[MWha^{-1}] = P_{therm}/1000[MW]2000[ha^{-1}]$	(Eq. 9)
	Technical energy potential	$E_{SCOP}[MWha^{-1}] = E_{therm}[MWha^{-1}](1 - SCOP^{-1})^{-1}$	(Eq. 10)

5.1.7 Thermal energy stored in fluid and solid phase E_{fluid}, E_{solid} and E_{total}

The energy content in the fluid phase E_{fluid} and in the solid phase E_{solid} for the time series from 2010 to 2015 can directly be derived from the 3D-THMs (cf. Table 5.3). This allows determining the thermal utilization potential during the course of the year. E_{total} is the sum of E_{fluid} and E_{solid}.

The ratio of E_{fluid} and E_{solid} illustrates the relationship between the energy stored in the different phases. The lower the value of the ratio the more energy is stored within the solid relative to the fluid phase. Together with the preceding indicators this ratio allows comparing the potential for 'active' and/or 'passive' energy uses in the different city quarters.

5.1.8 Technical potentials $Q_{tech}; P_{therm}; E_{therm}; E_{SCOP}$

Based on the numerical 2D-BM models and the thereby calculated technical flow rate potential Q_{tech}, additional measures for the 'active' thermal use of groundwater can be derived.

(A) The thermal power potential P_{therm} is the power of the geothermal heat source, which is calculated by the temperature spread ΔT and the volumetric heat capacity of water (cf. Eq. (8) in Table 5.3). For the case study of Basel, two scenarios were defined. First, a heating potential assessment with a ΔT of $5K$ that restores the assumed natural state T_{Nat} of 10°C from the initial mean TGW of 15°C and second, a peak extraction scenario with a ΔT of $8K$ (difference of current to T_{Nat} plus permitted temperature change of $3K$) were chosen.

(B) The thermal energy potential E_{therm} is an estimation of the annual amount of energy that would be abstracted by a common domestic GWHP for heating. Based on the VDI Guideline 4640 'Subsurface Thermal Use' a value of 2000 full load hours per year is defined.

(C) To derive the technical energy potential E_{SCOP} we apply the seasonal coefficient of performance (SCOP, DIN EN 14,825) that can accommodate seasonal variations and is a meteorological data weighted mean of the coefficient of performance (COP). In the medium term, the SCOP will replace the COP as an efficiency criterion for heat pump labelling. Whereas, for new constructions configuration values for SCOP can be in the order of 4, we apply a more conservative SCOP value of 3 which thereby also corresponds to existing building stocks. This means, that the heat delivered by the heat pump is 3 times the external energy supplied. The heating demand E_D of a building (Swiss Society of Engineers and Architects rule SIA 384/2) is $100kWhm^{-2}a^{-1}$. Therefore, a one-family house of $150m^2$ thus has a heating demand of $150{,}000kWh$ per year. For our evaluations we derive the surface to be heated A_{heat} in $[m^2]$ and discuss the number of one-family houses that can be supplied.

5.2 Modelling approach

The developed modelling tools for the different investigated scales and SGE systems, involve regional city-scale and quarter-scale high-resolution groundwater flow and heat transport models (3D-THM), 2D box models (2D-BM) on the quarter-scale as well as conceptual 3D-THM to study 'passive' installations of energy absorbers.

5.2.1 3D-THM for regional management-scale energy potential assessment

For four GWBs of the urbanized area of Basel high-resolution 3D-THMs were set up in FEFLOW© (cf. Fig. 5.1). Details on the model setup and parameterization of the model including boundary conditions can be found in the publications by Epting et al. (2017a) and Mueller et al. (2018). Based on these models, the groundwater flow regime and thermal potential was systematically evaluated for the entire urban area and selected city quarters in Basel.

In Epting et al. (2018b) the groundwater heat-potential was related to the heat-demand on the city-scale. Berger et al. (2011) provided the basis by estimating the today's and future's heat-demand of Basel. Subsequently, the results of the 3D-THMs facilitated to assess the heat-potential of the urban groundwater resources. The share of renewable energy that could be supplemented by using 'waste heat' from groundwater resources were estimated by merging heat-potential and heat-demand. Furthermore, the temporal evolution of heat-potential for selected city quarters (Q8 & Q11, Fig. 5.1) was exemplified and the capacity for space heating with typical annual heat-demand profiles was discussed.

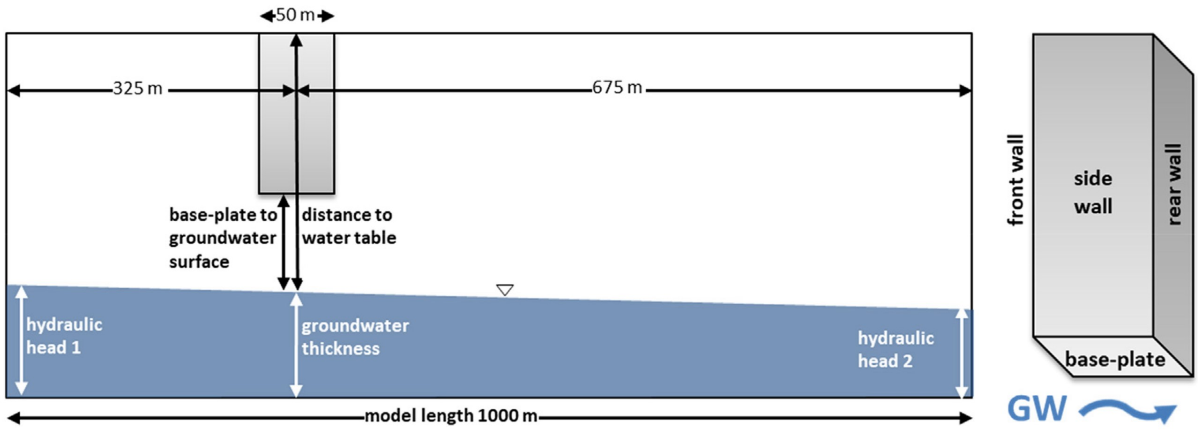

Figure 5.3: Geometric setup of conceptual 3D-THM including building structure and parametrization of model boundaries (from Epting et al. (2017b)). Right: Sketch of the different wall locations of a building structure related to the groundwater flow direction.

5.2.2 2D-BM for deriving 'technical potentials' of open loop SGE systems

Within the framework of the EU-Interreg project GRETA (Casasso and Sethi, 2017b), the TAP-method (thermal aquifer potential) was developed by Böttcher et al. (2019). The method allows a spatial potential evaluation of thermal groundwater use with an inclusion of applicable legal and operational restrictions. Particularly for well doublets, the technically possible withdrawal and reinjection quantities are jointly considered in a technical flow rate potential.

The method is based on numerical 2D box models (2D-BM), which are used to evaluate dependencies through parameter variations. The numerical approach ensures that also non-linear relationships are taken into account. The simulation results from parameter variation studies are used in the method to define functions in a multiple regression analysis. These regression functions facilitate a straightforward integration in GIS-procedures for potential assessment, while reproducing the flexibility of the numerical approach. A sustainable operation of well doublets is ensured by three hydraulic constraints, which define three pumping rates accordingly. Depending on local hydrogeology, i.e. aquifer thickness, depth to water, hydraulic gradient and conductivity, the possible pumping rates are calculated until the respective constraining threshold is reached. For the case study of Basel, the constraint thresholds are defined according to local regulation and guidelines:

1. A tolerable drawdown in the extraction well of one third of the saturated groundwater thickness (cf. Eq. (4) in Table 5.3)
2. A tolerable water level rise in the injection well of 0.5 m below ground surface (cf. Eq. (5) in Table 5.3)
3. The prevention of a hydraulic breakthrough to exclude the risk of thermal recycling (cf. Eq. (6) in Table 5.3)

The lowest of these three related flow rates defines the technically feasible flow rate (Q_{tech}). The pumping rate, before a hydraulic breakthrough is reached, depends on the distance between the extraction and the injection well. Therefore, different well distances of 10, 20 and 50 m are evaluated, whereas it is assumed that the injection well is always placed down-gradient of the abstraction well. In order to consider the hydraulically influenced zone of differently sized well pairs in the spatial analysis, the resulting raster data sets have corresponding resolutions of 20, 40 and 100 m. Thereby, the technical flow rate potential adapts to the space consumption of a well doublet and allows spatial queries of the groundwater abundance. However, Q_{tech} cannot simply be summed up in spatial queries. The current evaluation does not include the development of thermal anomalies, which would interfere with down-gradient installations. Since it is not possible to build every system, only an aggregation of grid cells perpendicular to the groundwater flow would be adequate. In addition, it is necessary to investigate the risk of thermal influence on or from already installed systems (see Section 5.3).

Together with permitted temperature differences, the technical flow rates provide a subsurface energy potential for open loop systems in a defined area, i.e. a grid cell or a plot of land. The TAP-method was applied to the selected city quarters in Basel (cf. Fig. 5.1). The necessary hydrogeological data of all relevant input parameters was available from the 3D-THM (cf. Table 5.3). Further details on the methodical approach can be found in Böttcher et al. (2019).

5.2.3 Conceptual 3D-THM to study 'passive' installations of energy absorbers

In Epting et al. (2017b) a systematic evaluation of the thermal impact of subsurface building structures on urban groundwater resources was presented. Based on conceptual 3D-THM representative 'settings' for the urban area of Basel were investigated, including: (1) hydraulic gradients and conductivities, which result in different groundwater flow velocities; (2) aquifer properties like groundwater thickness to aquitard and depth to water table; and (3) constructional features, such as building depths and thermal properties of building structures. The article emphasizes the importance of considering the thermal impact of subsurface structures, which is commonly underestimated, because of a lack of information and reliable subsurface temperature data. In order to investigate the energy potential of 'passive' installations in the groundwater saturated and unsaturated zone similar conceptual 3D-THMs were set up. The steady-state flow and heat transport models were set up in FEFLOW© (Diersch, 2014). The extent of the 3D model domain was 1000 m length and 500 m width and discretized into a total of 28 layers (29 slices), 1 m thick each (Fig. 5.3). The unstructured triangular meshing routine resulted in 248,528 elements and 130,065 nodes. The lowermost layer accounts for heat storage processes in the underlying consolidated bedrock (Epting et al., 2013; Händel et al., 2013) and was uniformly set to 20 m thickness (hydraulic conductivity of $1.0 \times 10^{-9} ms^{-1}$). Compared to the previous parameter and sensitivity analysis the studied constructional features included the consideration of different installation depths of the subsurface structures with energy absorbers.

Further details on the set-up and parametrization of the model including boundary conditions can be found in (Epting et al., 2017b). Since relative temperature changes were considered, only the temperature boundary condition of the subsurface structure itself had to be defined. The simulated energy potentials (E_{pot}) then could directly be derived from the different scenario calculations (heat budgets across the temperature boundary condition of the subsurface structure). Groundwater temperature increase down-gradient can also be derived with the chosen procedure.

Compared to the scenarios and constraints presented in (Epting et al., 2017b), only the temperature difference between the subsurface structure and the groundwater was changed (cf. Table S1 in the SI). Here, the following values were taken into account: (1) ΔT of $5K$ between the mean groundwater temperatures TGW in the city of Basel of 15°C and an assumed natural groundwater temperature T_{Nat} of 10°C as well as (2) ΔT of 8, 10 and $12K$ for the evaluation of scenarios related to the legally permissible 3 K-change in 100 m down-gradient of the thermal impact location (Swiss Water Protection Act, GSchG (1991)).

Furthermore, different positions of the energy absorber in the subsurface structure were evaluated. In addition to the (1) baseplate, also absorbers located in (3) front, (4) rear and (5) side walls were simulated to identify the influence of a changing groundwater exposure on the thermal impact. Energy absorbers located in subsurface structures above and below the groundwater level were also evaluated separately.

5.3 Results

5.3.1 Hydraulic and thermal potential on the city-scale and of the 18 city quarters

In the following, the results of the hydraulic and thermal potential assessment are presented. First, the results on the city-scale provide a basis for an integration of the shallow geothermal

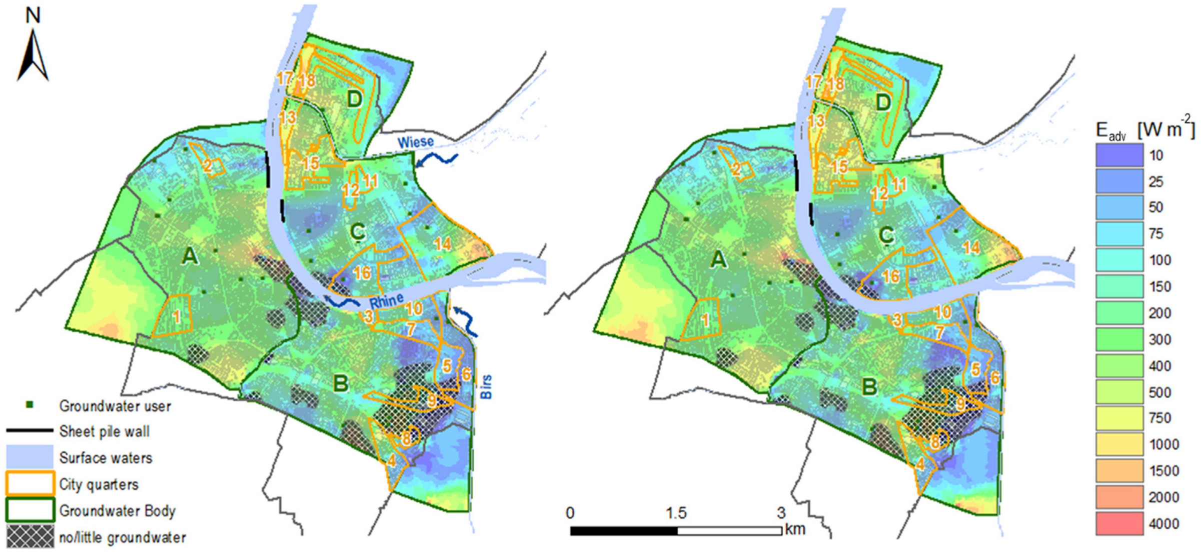

Figure 5.4: E_{adv} for 1^{st} July (left) and 31^{st} December (right) 2015. Black shaded: areas with little or no groundwater.

potential into urban energy planning of Basel. Second, water and energy balances of the 18 city quarters are derived by the previously described methods.

Fig. 5.4 shows the spatial distribution of E_{adv} for the whole modelled urban area of the city of Basel for the 1^st of July and 31^st December 2015, respectively. On average, E_{adv} in the study area amounts to $221Wm^{-2}$ (sd: $225Wm^{-2}$) in summer and to $229Wm^{-2}$ (sd: $243Wm^{-2}$) in winter, respectively.

As a result of large groundwater flow volumes and high temperature gradients near to the rivers Rhine and Wiese (GWBs D and C in single city quarters, e.g. Q14 and Q15), E_{adv} reaches values above $600Wm^{-2}$. Contrary, in the city quarters Q3 and Q8 located in GWB B, as a result of low groundwater flow volumes, E_{adv} is comparably low at values of about 10 to $50Wm^2$. Already this initial evaluation illustrates the groundwater heat potential for many areas in the urban aquifer of Basel.

Fig. 5.5 shows box plots of V_{fluid} and E_{total} distribution in the city quarters for the time-period 2010 to 2015. Table 5.4 summarizes the mean values for E_{fluid} and E_{total} for the selected city quarters. Remarkably large values for V_{fluid} and E_{total} can be observed in the city quarter Q14, which is located within the influence area of a hydropower plant and the impoundment of the river Rhine. Large hydraulic gradients up- to downstream of the impoundment result in an elevated exchange of surface water and groundwater and in dependence of the season higher temperature gradients. In the city quarters Q3, Q8 (GWB B), and Q18 (GWB D) groundwater flow is comparably low, resulting in low values for V_{fluid} and hence low values for E_{total}.

5.3.2 Technical potential of selected city quarters

Fig. 5.6 (left) shows the spatial distribution of the technical flow rate potential Q_{tech} calculated with the 2D-BM for the 18 city quarters at a well distance of 10 m. As observed for the advective heat transport, also Q_{tech} is comparatively high in the city quarters right of the river Rhine (GWBs C & D). Additionally, higher values can be found the river impoundment (southeastern edge of Q14) and at locations for which comparatively high hydraulic conductivities were calibrated (Mueller et al., 2018). Left of the river Rhine in GWBs A & B comparatively high values of Q_{tech} can be observed in the city quarters Q1 and Q10.

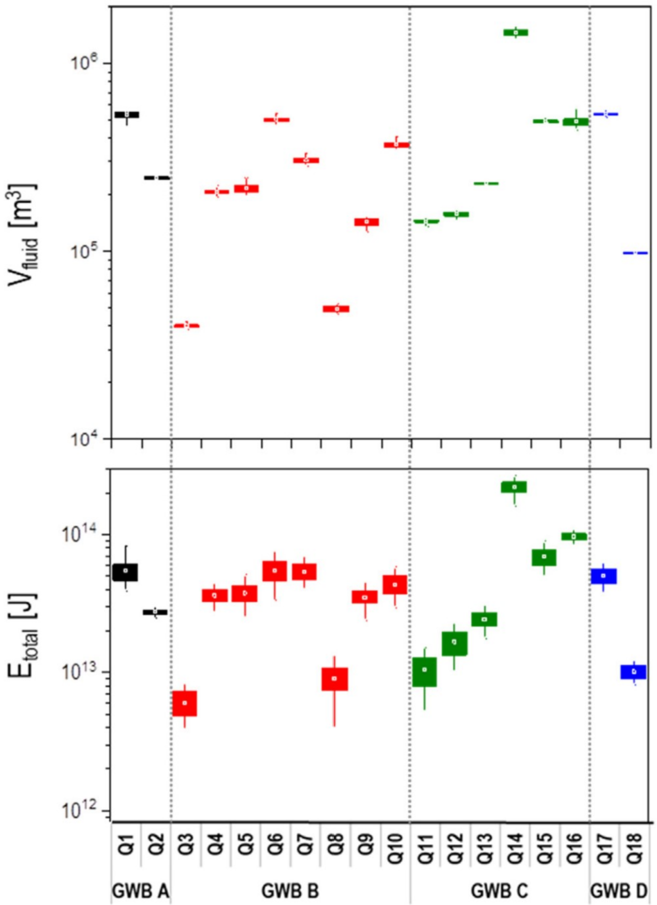

Figure 5.5: Statistics of V_{fluid} (above) and E_{total} (below) for the time period 2010 to 2015 in the selected 18 city quarters and GWBs (A - D). The boxplots show, the 1^{st} and 3^{rd} quartiles (box) as well as the upper and lower whiskers (1.5 * sd; horizontal bars outside of the box).

Exemplarily for city quarter Q1 the thermal power potential P_{therm} is illustrated for the evaluated well distances of 10, 20 and 50 m P_{therm} is calculated with a temperature difference of $5K$ and the previously derived values of Q_{tech} (cf. Fig. 5.6). For well distances of 10, 20 and 50 m P_{therm} amounts from 11 to $30kW$, 22 to $60kW$ and 45 to $141kW$, respectively. The calculations are also conducted with a ΔT of $8K$ for peak extraction estimates, where P_{therm} increases linearly.

As summarized in Table 5.1, aquifer thickness and depth to water are sufficient for an extraction and injection of groundwater in the city quarter Q1. Therefore, at comparatively small well distances of 10 and 20 m, the hydraulic breakthrough is the limiting threshold for a sustainable pumping rate. The larger well distance of 50 m allows significantly higher flow rates until a hydraulic breakthrough is generated. Due to a highly variable groundwater thickness of 2.7 to 6.3 m in Q1, the threshold of one third drawdown limits the extraction of groundwater in areas where the aquifer thickness is below approximately 3.5 m. This applies to the centre of Q1, mostly where P_{therm} values are below $100kW$. The technical flow rates of remaining north-western and southeastern parts are still constrained by a hydraulic breakthrough. Since in Q1 a rather large depth to the groundwater can be observed, the injection constraint is not relevant in this area (cf. Table 5.1).

Fig. 5.7 shows the average energy potentials E_{SCOP} for each city quarter. On the left side of the river Rhine (GWBs A & B) only city quarter Q1 shows relatively high energy potentials. In comparison, right of the river Rhine (GWBs C & D) high E_{SCOP} can be observed for all city quarters except for Q16. Those high potentials result mainly from a combination of elevated hydraulic conductivity and aquifer thickness.

5.3.3 Potential of energy absorbers in the subsurface

Table S1 in the supplementary material summarizes the calculated scenarios and the simulation results of the conceptual models for the evaluation of energy absorber potential in the subsurface. Generally, the highest E_{pot} can be observed for energy absorbers installed within the baseplate. As soon as the subsurface structure (scenarios 3) reaches into the groundwater saturated zone, the highest E_{pot} can be observed for the front wall. The lowest E_{pot} values resulted

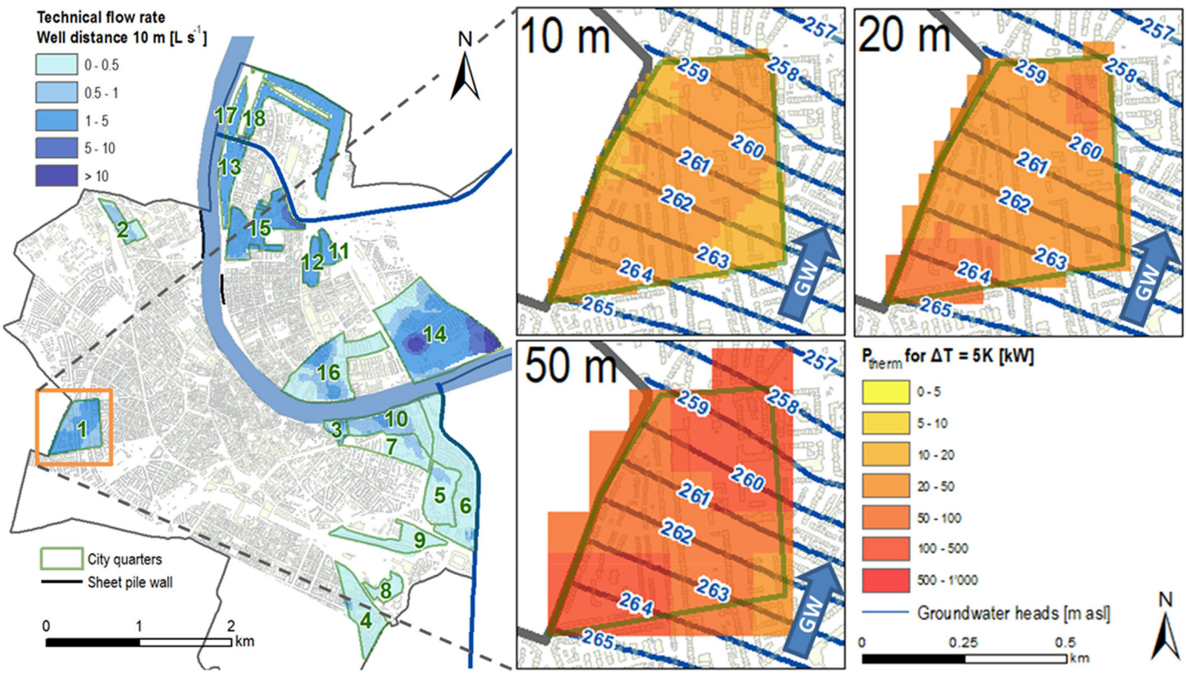

Figure 5.6: Results of 2D-BM. Left: Q_{tech} calculated for the 18 city quarters for a well distance of 10 m; orange rectangle highlights city quarter Q1 for the detailed presentations on the right. Right: E_{tech} for 'heating' calculated for well distances of 10, 20 and 50 m and for a ΔT of 5 K (please note differences in grid cell resolution).

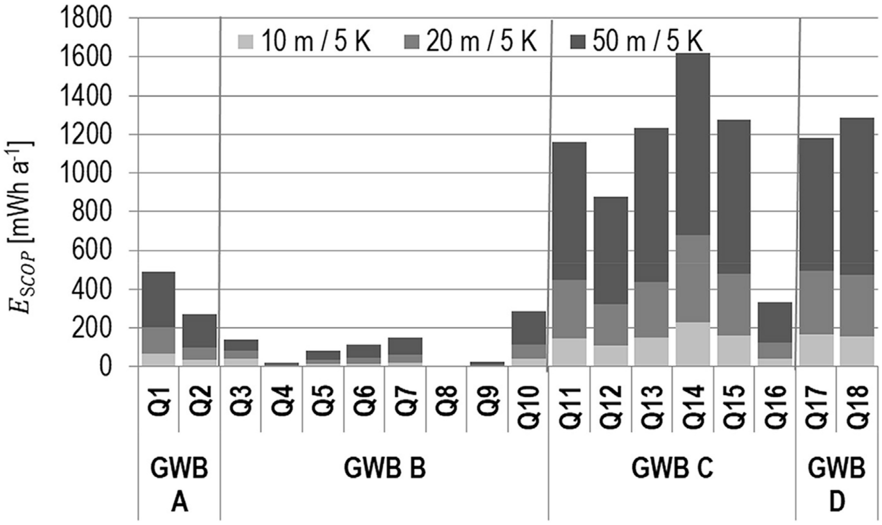

Figure 5.7: Average E_{SCOP} for 'heating' in the 18 city quarters of the 4 GWBs for well distances of 10, 20 and 50 m and a ΔT of 5 K. Calculated from average E_{pot} assuming 2,000 full load hours per year and after consideration of a SCOP of 3.

in scenarios for the rear wall. In all cases, E_{pot} of the subsurface structure in the groundwater saturated zone is orders of magnitude higher compared to those in the non-saturated zone.

Fig. 5.8 shows the total E_{pot} for the calculated scenarios. High values of E_{pot} with 30 to $40 Wm^{-2}$ can be observed for the scenario 2.2 with very high hydraulic conductivities as well as for the scenarios 3.1, 3.4 and 3.6 with subsurface structures located within the groundwater. Still high values of 12 to $17 Wm^{-2}$ can be observed for higher ΔT between the subsurface structure and the groundwater (scenario 6.3). The remaining scenarios show comparably low values of E_{pot} in a range from 4 to $16 Wm^{-2}$ (cf. Fig. 5.7).

A consideration of the temperature changes 100 m down-gradient of the subsurface structure and 2 m below the groundwater table shows that only a few scenarios reach or exceed the legally relevant 3 K limit (Table S1 in the supplementary material). In summary, the derived energy potentials are plausible and in the same range as similar parameter studies (Brandl, 1998, 2016; Di Donna et al., 2017; Amis et al., 2010; Brandl et al., 2010; Markiewicz, 2004; Sun et al., 2013; Xia et al., 2012).

Table 5.4: Derived feasibility indicators for the 18 city quarters and the different modelling approaches.

GWB	**City quarter [Q]**	E_{fluid} $[J]$	E_{solid} $[J]$	E_{total} $[J]$	E_{fluid}/E_{solid} $[-]$	E_{adv} $[Wm^{-2}]$	Q_{tech} $[ls^{-1}]$	P_{therm} $[kW]$	E_{SCOP} $[MWha^{-1}]$	A_{heat} [a] $[m^2]$	**Thermal use**
A	①	$3.7-6.0\times10^{12}$	$3.5-9.2\times10^{13}$	$3.9-9.5\times10^{13}$	0.09	200 – 250	0.54 – 1.45	11 – 30	66.20	662	„active“
	②	$2.5-2.8\times10^{12}$	$2.2-2.8\times10^{13}$	$2.5-3.0\times10^{13}$	0.11	60 – 140	0.33 – 0.65	7 – 14	33.07	331	„active“
B	③	$3.2-7.6\times10^{11}$	$3.2-7.1\times10^{12}$	$3.9-8.6\times10^{12}$	0.09	75 – 400	0.09 – 2.02	0 – 39	38.83	388	„passive”
	④	$1.4-2.4\times10^{12}$	$2.3-3.8\times10^{13}$	$2.7-4.6\times10^{13}$	0.06	25 – 500	0 – 1.15	0 – 24	4.16	42	„passive”
	⑤	$1.6-2.8\times10^{12}$	$2.1-4.3\times10^{13}$	$2.5-5.2\times10^{13}$	0.07	10 – 100	0 – 0.81	0 – 17	12.32	123	local „active“
	⑥	$3.8-6.9\times10^{12}$	$2.8-6.5\times10^{13}$	$3.3-7.7\times10^{13}$	0.12	10 – 100	0 – 1.24	0 – 23	15.24	152	local „active“
	⑦	$2.3-3.8\times10^{12}$	$3.3-5.9\times10^{13}$	$4.0-7.0\times10^{13}$	0.07	10 – 250	0 – 2.71	0 – 26	20.16	202	local „active“
	⑧	$1.8-6.5\times10^{11}$	$3.3\times10^{12}-1.2\times10^{13}$	$3.9\times10^{12}-1.4\times10^{13}$	0.05	10 – 300	0 – 0.06	0 – 1	0.12	1	„passive”
	⑨	$9.8\times10^{11}-2.0\times10^{12}$	$2.0-3.9\times10^{13}$	$2.4-4.7\times10^{13}$	0.05	50 – 200	0 – 0.50	0 – 10	3.75	38	„passive”
	⑩	$2.9-4.8\times10^{12}$	$2.5-4.9\times10^{13}$	$2.9-5.9\times10^{13}$	0.11	20 – 200	0.12 – 1.23	1 – 26	38.31	383	„active“
C	⑪	$6.7\times10^{11}-1.4\times10^{12}$	$5.2\times10^{12}-1.5\times10^{13}$	$5.2\times10^{12}-1.5\times10^{13}$	0.09	100 – 300	1.45 – 4.44	30 – 93	147.30	1473	„active“
	⑫	$1.1-1.6\times10^{12}$	$1.0-2.3\times10^{13}$	$1.0-2.3\times10^{13}$	0.08	70 – 300	1.08 – 2.97	23 – 62	107.46	1075	„active“
	⑬	$2.1-3.6\times10^{12}$	$1.8-3.2\times10^{13}$	$1.8-3.2\times10^{13}$	0.12	100 – 800	1.27 – 7.65	27 – 160	148.33	1483	„active“
	⑭	$1.1-1.7\times10^{13}$	$1.6-2.7\times10^{14}$	$1.6-2.7\times10^{14}$	0.06	30 – 2300	0.21 – 59.34	4 – 1242	227.27	2273	„active“
	⑮	$4.5-7.5\times10^{12}$	$4.9-9.0\times10^{13}$	$4.9-9.0\times10^{13}$	0.09	300 – 1400	0.77 – 9.42	16 – 197	160.81	1608	„active“
	⑯	$4.9-6.8\times10^{12}$	$8.2\times10^{13}-1.1\times10^{14}$	$8.3\times10^{13}-1.1\times10^{14}$	0.06	10 – 200	0 – 5.46	0 – 114	41.00	410	„active“
D	⑰	$3.5-5.4\times10^{12}$	$3.5-6.3\times10^{13}$	$3.6-6.4\times10^{13}$	0.09	70 – 700	1.43 – 9.20	30 – 193	166.10	1661	„active“
	⑱	$1.0-1.6\times10^{12}$	$8.0\times10^{12}-1.2\times10^{13}$	$8.2\times10^{12}-1.2\times10^{13}$	0.03	50 – 800	1.03 – 4.92	22 – 103	157.13	1571	„active“

[a] Assuming that the heating demand E_D of a building is $100kWhm^{-2}a^{-1}$ (Swiss Society of Engineers and Architects rule SIA 384/2).

5.3.4 Joint evaluation of hydraulic and thermal potentials for the different city quarters

In the following a joint evaluation of hydraulic and thermal potentials for the different city quarters is presented, whereas also the interaction with existing subsurface use is considered. The values for P_{therm} and E_{pot} are calculated for an exemplary well distance of 10 m, a temperature difference of 5 K and 2,000 full load hours per year.

Table 5.4 summarizes the derived feasibility indicators for the different city quarters. On the basis of the presented evaluation, it can be deduced in which city quarters 'active' and/or 'passive' SGE systems, for the corresponding boundary conditions, are promising. Based on the calculations of technically feasible flow rates Q_{tech} the technical energy potential E_{SCOP}, the serviceable surface to be heated A_{heat} and the heat demand E_D as well as the number of single-family houses to be supplied by one well doublet with distances of 10 m could be derived.

The city quarters Q1 and Q2 in GWB A show that 'active' SGE systems are promising. An influence from already existing groundwater use north-west of city quarter Q2 could be expected, since it is positioned up-gradient (Fig. 5.1). However, this user reinjects comparatively 'warm' water into the aquifer and a 'positive' synergetic effect down-gradient is likely, thereby increasing the efficiency of SGE-systems for 'heating'. In city quarters Q3 to Q10 in GWB B 'active' SGE systems are not equally suitable.

In the city quarters Q3, Q4 and Q8 not even the smallest thermal loads can be covered by GWHP systems, whereas in sub-areas of the city quarters Q5 and Q 9 an 'active' SGE use for small domestic heating loads can be achievable. Although the city quarters Q6, Q7 and especially Q10 are suitable for small domestic GWHP systems in some areas, the interactions with existing thermal uses have to be considered (Fig. 5.1).

On the right side of the river Rhine, a larger potential for GWHP installations is present, here SGE systems for an 'active' energy use are promising in all city quarters. For the city quarter Q16 the interaction with an existing groundwater user has to be considered (Fig. 5.1). Also in city quarters Q17 and Q18 in GWB D 'active' energy use is favourable. Apart from city quarter Q1 in GWB A in vicinity of all city quarters one or more potentially contaminated sites are located and possible thermal and remobilization impacts have to be explored prior to the installation of new 'active' SGE systems.

5.4 Discussion

To date, comprehensive quantitative potential assessment concepts for the thermal use of groundwater, which are elementary for a sustainable use of any renewable energy resource, are rare (Böttcher et al., 2019). However, such concepts are fundamental for optimizing utilization strategies and their integration into spatial energy planning on the urban scale. In the work

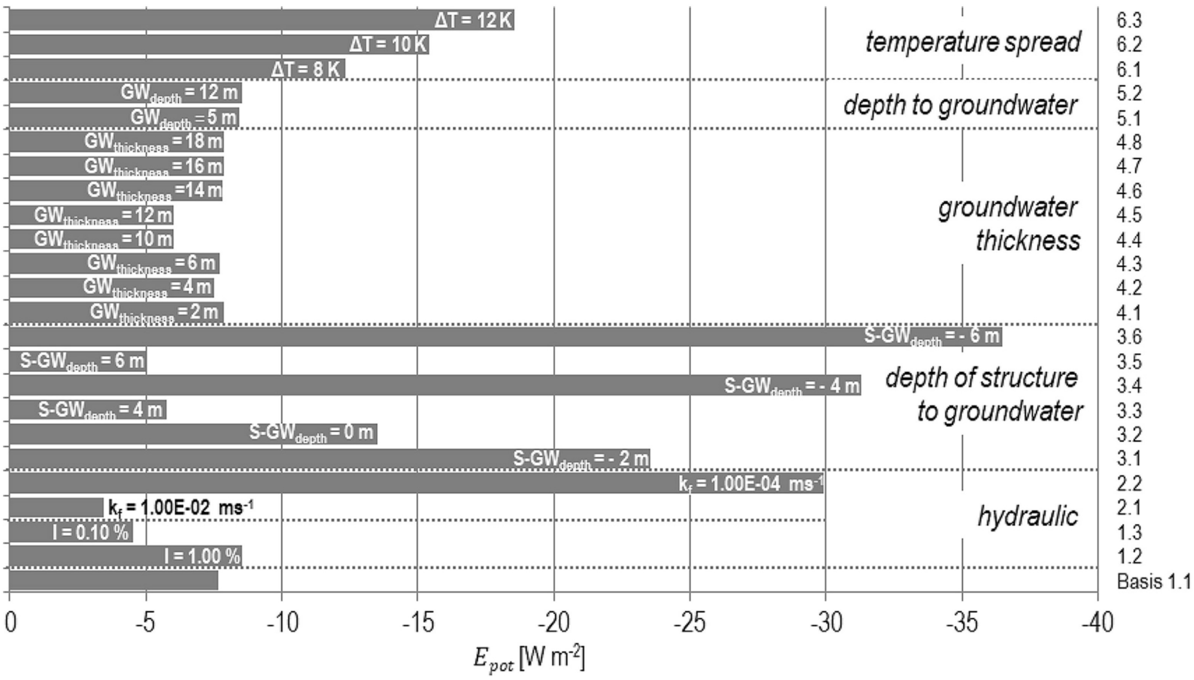

Figure 5.8: E_{pot} calculated for the different hydraulic and subsurface structural settings of energy absorbers. The Scenarios (right y-axis) include the different hydraulic and geometric settings of the subsurface structure related to the aquifer as well as the investigated ΔT (value ranges are provided within columns). The basis scenario 1.1 was calculated with $i = 0.5\%, k_f = 1.0e - 03ms^{-1}, GW_{thickness} = 10m, S - GW_{depth} = 2m$ and $\Delta T = 5K$.

of Bayer et al. (2019) different geothermal potentials beneath cities are categorized, including the theoretical, technical, economic and acceptable potential. The presented methods in this work illustrate approaches on how to assess the theoretical and technical geothermal potential on the urban scale. An assessment of these potentials is the basis for further analysis related to economic and acceptable potentials for a sustainable thermal use of urban subsurface resources.

5.4.1 Assessing theoretical potentials on the city-scale

Previous work (Epting et al., 2018a,b) has shown, that by means of high-resolution 3D-THMs the spatiotemporal regional groundwater flow and heat-transport regime of the shallow subsurface can be evaluated on the city-scale. Likewise, their application facilitates evaluations of the dynamics of hydraulic and thermal processes and the numerous interactions of the different natural and anthropogenic boundary conditions. Since the 3D-THMs have been calibrated and validated against high-resolution datasets covering main state variables for flow and heat-transport problems, the uncertainty assumed is considerably lower than using analytical approaches from other methods. Furthermore, potential assessment studies should be continuously updated in order to follow city development, which is highly dynamic even at shorts periods of time. If city planners need to adapt their renewable action plans to changes in urban development, a 3D-THM approach like the one presented in this work would be favourable.

5.4.2 Advancement of 'technical potential' assessment

The 2D-BMs involve the relevant regulative, operational and spatial constraints and link evaluated technical flow rates to a thermal impact assessment, the methodology is only suitable for unconfined porous aquifers with a certain hydrogeological homogeneity and in the absence of complex boundary conditions, because the simulations were conducted in idealized box-models in steady-state conditions (Böttcher et al., 2019).

Preceding potential assessment studies concentrated on budgeting approaches (Arola et al., 2014; Rauch and Stegner, 2004; Götzl et al., 2014) and sustainable volume flow estimations as specific constraints (Casasso and Sethi, 2017a; García-Gil et al., 2015a). Especially the definition of drawdown limits, in dependence of the aquifer thickness, is common to estimate reliable well yields (García-Gil et al., 2015a; Misstear and Beeson, 2000). However, only considering a drawdown constraint is not coping with the technical requirements for a sustainable operation, particularly in high transmissivity zones (García-Gil et al., 2015a). Thus, the applied TAP method also includes a threshold for the groundwater table rise at the injection well to prevent flooding of the surface or basements. Further, the space consumption, i.e. the hydraulic footprint, of a well doublet is related to the well distance. An integration of the hydraulic footprint assures that an operation without a considerable hydraulic breakthrough will still be possible for densely spaced well doublets (Böttcher et al., 2019). Considering the hydraulic breakthrough provides a conservative threshold to avoid thermal recycling (Galgaro and Cultrera, 2013; Casasso and Sethi, 2015) as it occurs before a thermal breakthrough (thermal retardation). For all introduced constraints, the TAP-method considers the mutual interference between the wells through the numerical parameter study, which provides a specific adaptation to GWHP systems.

5.4.3 Potential risks & reconsideration of existing regulations

By following a holistic approach, risks related to contaminated sites and impacts on existing subsurface and groundwater use in the neighbourhood of possible new installations were discussed for the selected city quarters. In vicinity of all investigated city quarters of Basel potentially contaminated sites are located, and possible thermal remobilization impacts have to be explored prior to the installation of new 'active' SGE systems. Since GWHP systems often have large pumping capacities and displace relatively large volumes of groundwater the influence on contaminants can be a crucial barrier for the realization of new systems (Zuurbier et al., 2013).

The results show a generally large potential for the use of SGE in the city quarters of Basel. Especially for the investigated city quarters on the right side and in the vicinity of the rivers Rhine and Wiese the installation of 'active' GWHP systems is favourable. However, the comparative analysis revealed that the potential of open loop systems is highly variable between the quarters and thus, the application of 'passive' energy absorbers can be preferable at specific sites. In detail, the evaluation of 'passive' energy use in the subsurface building envelope illustrates the high energy potentials of installations within the baseplate and installations reaching into the groundwater saturated zone. Thereby, our evaluations also allow the identification of city quarters for which the realization of networks with different energy supply systems could be achievable.

Another focus should be placed on the reconsideration of existing regulations. Today, a lack of knowledge can stimulate a highly precautionary approval attitude and a strict regulation, in which case the geothermal potential of cities remains underused (Haehnlein et al., 2010). Based on our research, the city of Basel already loosened restrictions concerning thermal groundwater use. Particularly, the hard threshold for reinjection temperatures of ± 3 K difference compared to the 'natural' background temperature in 100 m down-gradient of the thermal impact has been relaxed. Nowadays, GWHP systems used for heating purposes are generally privileged and the reinjection of comparably 'cold' water into the aquifer is allowed for temperature differences even below $-5K$. Also in the Netherlands new legislation supports ATES (aquifer thermal energy systems) systems with a balanced energy budget and systems that may effectively cool the subsurface by injecting a surplus of cold (net heat extraction over the years; Drijver and Godschalk (2018)).

5.5 Conclusions

The modelling approaches presented in this study integrate the requirements for applications in energy planning at different spatial scales, including the city-scale and the scale of city quarters. Solutions for the energy use in the shallow urban subsurface target on deriving the energy potential by means of a combination of numerical high-resolution 3D groundwater flow and heat transport models as well as 2D box models.

Furthermore, the technical potential for 'active' (open loop groundwater use by well doublets) and 'passive' (energy absorbers) use was assessed. The investigations focused on a systematic evaluation of different parameters for evaluating energy potentials of the urban area of Basel (Switzerland) as well as for 18 selected city quarters. The studied parameters include the advective energy transport E_{adv} with groundwater flow as well as a differentiation between thermal energy stored in the fluid phase, the solid phase and their sum E_{fluid}, E_{solid} and E_{total} as well as the energy potential E_{pot} of absorber systems installed in subsurface building envelopes. Furthermore, for the individual city quarters technically feasible flow rates Q_{tech} could be derived which allowed to calculate different energy potentials, including the thermal power P_{therm} and energy potential E_{therm} as well as the technical energy potential E_{SCOP}. Those particularly developed potential measures are used to provide a comparative analysis of the energy potential for initial suitability considerations. The main technical aspects of the study are summarized in the following.

1. The presented thermal potential assessment of provides a scientific basis for the development of application-oriented management tools on the city-scale and the city quarter scale.

2. The city-scale 3D groundwater flow and heat-transport models allow assessing the energy potential by deriving heat flow densities for the entire urban area and to perform suitability analysis to optimize SGE system locations and operation by including the seasonal component of heat availability and demand.

3. The work quantifies and compares the technical potential of thermal groundwater use for 'heating' with well doublets and energy absorbers in 18 selected city quarters of Basel.

4. The availability of high-resolution data on aquifer thickness, hydraulic conductivity and groundwater levels assures a high comparability of the two approaches. For the investigated parts of Basel, areas with sufficient groundwater supply and high advective heat flux have been defined as suitable for the thermal use of groundwater with well doublets, whereas thermal power potentials can amount to $1242 kW$. Areas with low groundwater abundance, on the other hand, are more suitable for 'passive' geothermal applications and seasonal energy storage. Likewise, the installations of energy absorbers in building envelopes located within the groundwater can provide energy potentials of 4 and up to $40 Wm^{-2}$. For the evaluated city quarters possible conflicts and synergies between new installations and existing groundwater users are indicated.

With the presented results, architects, city planners and potential users can acquire initial site-specific information on the technical feasibility of SGE use in the context of city development and construction projects. In addition, the assessment results will support spatial planning and can be integrated into urban energy plans, which foster the use of renewable energy and reduce the use of fossil fuels.

5.6 Acknowledgements

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Chapter 6

Thermal influences on groundwater in urban environments – A multivariate statistical analysis of the subsurface heat island effect in Munich

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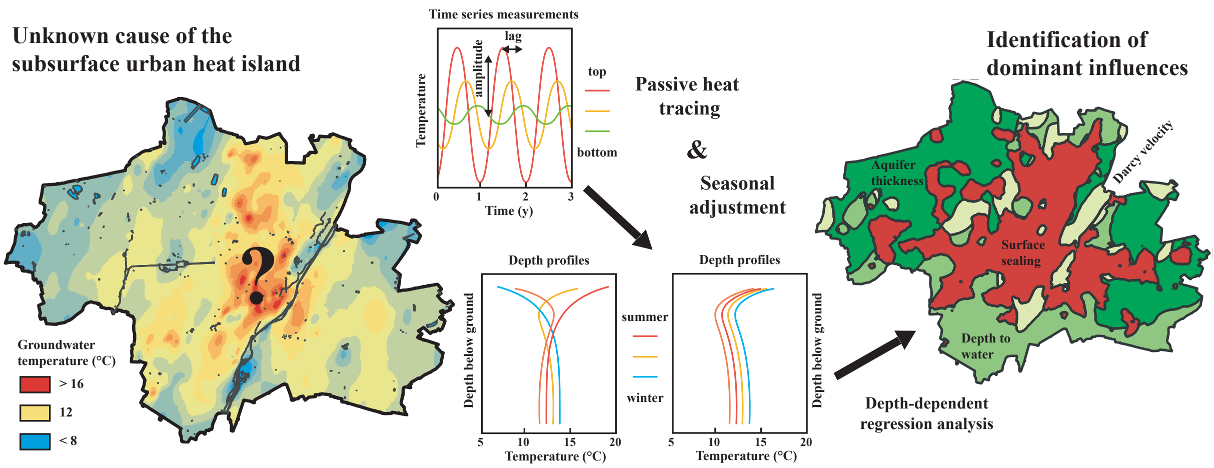
Graphical Abstract



Abstract

Shallow aquifers beneath cities are highly influenced by anthropogenic heat sources, resulting in the formation of extensive subsurface urban heat islands. In addition to anthropogenic factors, natural factors also influence the subsurface temperature. However, the effect of individual factors is difficult to capture due to high temporal dynamics in urban environments. Particularly in the case of shallow aquifers, seasonal temperature fluctuations often override the influence of existing heat sources or sinks. For the city of Munich, we identify the dominant anthropogenic and natural influences on groundwater temperature and analyse how the influences change with increasing depth in the subsurface. For this purpose, we use depth temperature profiles from 752 selected groundwater monitoring wells. Since the measurements were taken at different times, we developed a statistical approach to compensate for the different seasonal temperature influences using passive heat tracing. Further, we propose an indicator to spatially assess the thermal stress on the aquifer.

A multiple regression analysis of four natural and nine anthropogenic factors identified surface sealing as the strongest and the district heating grid as a weak but significant warming influence. The natural factors, aquifer thickness, depth-to-water and Darcy velocity show a significant cooling influence on the groundwater temperature. In addition, we show that local drivers, like thermal groundwater uses, surface waters and underground structures do not significantly contribute to the city-wide temperature distribution. The subsequent depth-dependent analysis revealed that the influence of aquifer thickness and depth-to-water increases with depth, whereas the influence of Darcy velocity decreases, and surface sealing and the heating grid remain relatively constant. In conclusion, this study shows that the most critical factor for the mitigation of future groundwater warming in cities is to minimize further sealing of the ground, to restore the permeability of heavily sealed areas and to retain open landscapes.

Keywords : Groundwater temperature, urban heat island, temperature time series, temperature-depth profile, passive heat tracing

6.1 Introduction

Cities are usually warmer than their rural surroundings (Oke, 1982). This phenomenon is known as the "urban heat island", and it is present in the atmosphere, on the surface and in the subsurface as the so-called subsurface urban heat island (SSUHI) (Gunawardhana et al., 2011; Oke et al., 2017). Thus, in cities with shallow aquifers, valuable groundwater resources are exposed to numerous anthropogenic impacts (Epting et al., 2013; Menberg et al., 2013b). Elevated temperatures can affect groundwater quality, microbial ecosystems or contaminant transport (Brielmann et al., 2009; Bonte et al., 2013; Jesußek et al., 2013a; García-Gil et al., 2018). Furthermore, despite the influence on the resource itself, studies have highlighted the additional risk of drinking water quality degradation by elevated ground temperatures as water travels through the drinking water distribution system (Müller et al., 2014; Agudelo-Vera et al., 2020). Therefore, it is essential to gain deeper insights into how the different thermal sources and sinks affect subsurface and groundwater temperatures and support the development of adequate measures for the future protection of urban groundwater bodies (Ferguson and Woodbury, 2007; Eggleston and McCoy, 2015; Zhu et al., 2015; Benz et al., 2017; Epting et al., 2017b).

While an increasing amount of SSUHI phenomena are described around the world (Taniguchi et al., 2005, 2009; Yalcin and Yetemen, 2009; Lokoshchenko and Korneva, 2015; Bucci et al., 2017; Marschalko et al., 2018; Visser et al., 2020), studies have already identified a set of related anthropogenic heat sources (Menberg et al., 2013b). Primarily, heat loss from buildings and higher ground surface temperatures resulting from changed land use are held accountable for elevated subsurface temperatures (Ferguson and Woodbury, 2004; Reiter, 2007; Benz et al., 2018; Hemmerle et al., 2019). Furthermore, previous work successfully introduced methods to quantify anthropogenic heat fluxes through analytic calculations (Menberg et al., 2013b; Benz et al., 2015).

In addition, the groundwater temperature is a governing factor for the efficiency of thermal use. Thus, the SSUHI promotes and is also remediated by installing groundwater heat pumps (Allen et al., 2003; Zhu et al., 2010; Epting and Huggenberger, 2013; Rivera et al., 2017b). In contrast, groundwater use for cooling is hampered, whereas the cooling demand in cities is likely to increase in the future (Li et al., 2019; van Ruijven et al., 2019). As a result, the controversial discussion about the growth of new groundwater cooling systems will benefit from a more precise understanding about the magnitude of thermal influences on large scale (Blum et al., 2010; Visser et al., 2020).

The thermal characterisation of shallow aquifers remains challenging because groundwater temperatures at depths of up to 10 to 20 m are influenced considerably by seasonal temperature variations on the surface (Banks, 2009a; Stauffer et al., 2014; Farr et al., 2017). In shallow aquifers below urban areas, seasonal variations coincide with various anthropogenic heat sources, like for example sealed surfaces or subsurface building parts. This results in highly dynamic and complex thermal conditions, where identifying influencing heat sources is not straightforward (Ferguson and Woodbury, 2007; Taniguchi et al., 2007). In detail, single measurements within the seasonal fluctuation zone do not represent the undisturbed conditions required, e.g. the annual mean temperature, to link elevated ground temperatures to specific influences (Menberg et al., 2013a). To circumvent this problem, studies commonly rely on deeper measurements underneath the zone of seasonal variations ($> 15m$) to analyse the dependency between heat sources near the surface and groundwater temperatures (Benz et al., 2016, 2018; Hemmerle et al., 2019). Shallow aquifers have not been extensively studied despite their importance, e.g., for thermal use or water for domestic or industrial use. In addition, the interpretation of groundwater temperatures closer to the ground surface is potentially beneficial for revealing the impact of specific heat sources and detecting climate-induced short-term changes. Previous research has largely been focused on evaluating the anthropogenic causes of the SSUHI effect. However, especially in hydraulically conductive gravel aquifers, it is assumed that the intensity of the SSUHI further depends on hydrogeological properties like the thickness of the saturated zone, depth-to-water or groundwater velocity (Epting et al., 2013; Bidarmaghz et al., 2019). Hence, a comparative analysis of hydrogeological and anthropogenic factors based on a large dataset of measurements can contribute to a deeper understanding of increasing and decreasing influences on groundwater temperatures and help to establish measures to mitigate increasing groundwater temperatures in cities.

The thermal conditions of Munich's quaternary aquifer were previously assessed and discussed by Dohr (1989, 2011)), Dohr and Gruban (1999) and Zosseder et al. (2013). As early as the first study, the anthropogenic heat influence was recognised and various sources were identified. During the construction of the subway, measurements in the surroundings of the tunnels revealed a considerable local temperature increase (1.0°C – 2.0°C) in the groundwater (Dohr, 1989). Spatially distributed measurements showed that temperatures gradually increase towards the city centre with locally cooler areas in parks (Dohr and Gruban, 1999). Thus, building density and surface sealing were assumed to play a significant role, whereas previous studies were unable to prove beyond doubt any relevant influence of the district heating grid, the sewerage or the infiltration systems. Strong local thermal influence is further attributed to the river Isar and large subsurface buildings which partially reach into the groundwater body.

With a more precise knowledge about the properties of the aquifer and its use, an influence of saturated groundwater thickness and large thermal uses for cooling became apparent (Böttcher et al., 2019; Albarrán-Ordás and Zosseder, 2020; Theel et al., 2020). However, these hypotheses were mainly tested by interpreting individual measurements and have never been analysed comparatively using all the historical and recent temperature datasets to gain quantitative statistical measurements about the intensity of all potential influences. Furthermore, temperature datasets with a vertical resolution, like the depth profile measurements used, have not been available before. As a result, previous studies had to rely on spatially interpolated measurements taken 1 m below the groundwater level and mainly lie within the zone of seasonal fluctuations (Dohr, 1989, 2011; Dohr and Gruban, 1999).

To tackle the shortcomings mentioned, we investigated the seasonal fluctuations in the shallow gravel aquifer of the city of Munich with a data basis of 71 multi-annual groundwater temperature time series. Subsequently, we estimated the mean thermal diffusivity with passive heat tracing and used the information derived on seasonal fluctuations to adjust a city-wide dataset of 752 vertical temperature profiles originating from different measurement times on one reference date to reproduce the same seasonal state. With this seasonally corrected dataset, we identified the dominant large-scale and local-scale drivers of the SSUHI effect by multiple linear regression. Finally, we analysed the depth-dependent measurements statistically to show vertical changes in the magnitude of the previously identified five dominant natural and anthropogenic influences.

The study presented in this paper assesses the natural and anthropogenic thermal influences on the shallow aquifer of Munich, proposes an approach to adjust the seasonal variation of temperature measurements to the same seasonal state and highlights the mitigating role of hydrogeological properties in the context of anthropogenic groundwater warming.

6.2 Materials and methods

6.2.1 Climatic and hydrogeological overview of the study site

The city of Munich lies in the south of Germany, about 50 km north of the Alps. With over 1.5 million inhabitants, it is the most densely populated city and one of the fastest-growing municipalities in Germany. Munich has a warm-summer humid continental climate with a mean annual precipitation of approx. 950 mm (1977-2000) and a mean air temperature of 9.5°C (1955-2018) (Peel et al., 2007; Mühlbacher et al., 2020). The city's air temperature shows a significant upward trend of 0.31°C per decade over the reference period (1955-2018). In line with this observation, a decrease in the number of frost days with air temperatures below freezing and an increase in the number of summer days with a maximum temperature of at least 25°C was recognised in the long-term trends. The occurrence of summer days rose from 28 in 1955 to 60 in 2018 and frost days declined from 95 in 1955 to 68 in 2018. Measurements by the German Weather Service also show that the city's nightly air temperatures are on average 1.7 K higher than the nearby rural areas (Mühlbacher et al., 2020). Due to its green spaces and large parks, no continuous heat island forms over the entire city (cf. Figure 6.1e). Elongated areas, like the north-south oriented bed of the river Isar, contribute largely as pathways for the flow of cold air into the city. Thus, the heat island of Munich is compartmentalised and subject to a great number of local and regional exchange processes (Funk et al., 2014). This situation is certainly reflected in the subsurface.

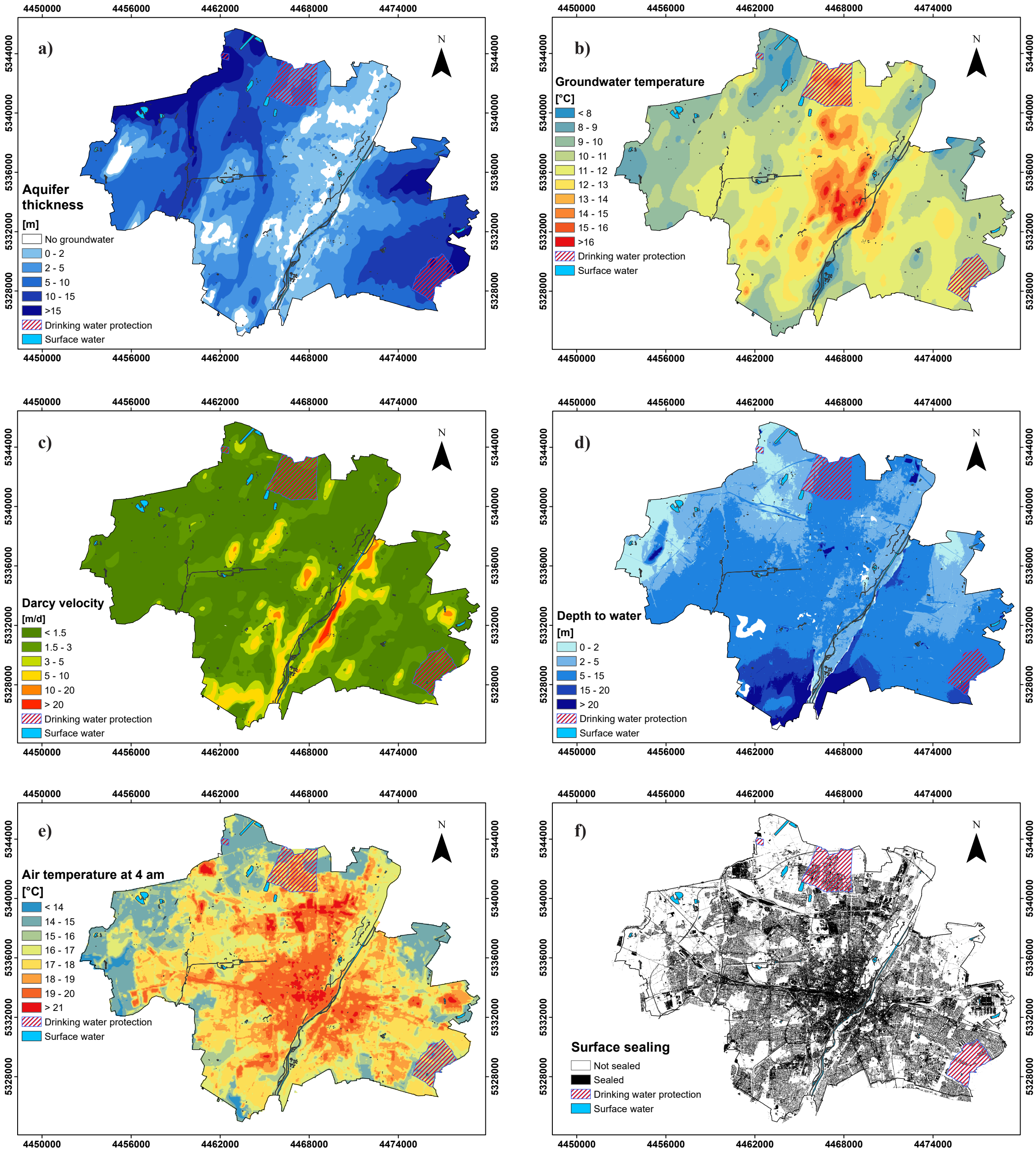


Figure 6.1: City-wide datasets of a) saturated aquifer thickness of the quaternary groundwater, b) groundwater temperature measured in April 2014 one metre below groundwater level, c) Darcy velocity, d) depth-to-groundwater, e) Modelled air temperature 2 m above ground at 4 am in summer adapted from Funk, Groß and Trute (2014) and f) surface sealing (cf. Section 2.2.3).

The city lies at a mean altitude of 519 metre above sea level (m.a.s.l.) on the so-called Munich Gravel Plain, which dips northwards by about 0.5 percent. Its present shape evolved primarily during the Pleistocene period when large amounts of fluvioglacial sandy gravel were deposited on the former Tertiary landscape (Jerz, 1993). Due to the past drainage system, the morphology of the Tertiary surface is characterised by an uneven relief of channels and ridges (Kerl et al., 2012; Albarrán-Ordás and Zosseder, 2020). The limno-fluviatile Tertiary sediments are mainly composed of fine sand with a varying silt content intersected by silt and clay layers (Lemcke, 1988). In comparison with the overlying gravels, the hydraulic conductivity of the Tertiary layers is generally two to five orders of magnitude lower and, consequently, the Tertiary sediments mostly confine the quaternary groundwater towards the bottom (Jerz, 1993; Zosseder, 2007). As a result, Figure 6.1a shows that the saturated thickness of the quaternary aquifer, derived from mean low water conditions, varies largely throughout the city area with a 1^{st} quartile of $2.5m$ and a 3^{rd} quartile of $10.2m$ (Albarrán-Ordás and Zosseder, 2020; Theel et al., 2020). In general, the gravel sediments form a productive aquifer with an average hydraulic conductivity of $3.7 \times 10^{-3} m/s$ based on the hydrofacies types occurring (Theel et al., 2020). As displayed in Figure 6.1c and Figure 6.1d, a high average Darcy velocity with a mean of $1.8m/d$ (1^{st} qu. 0.8 / 3^{rd} qu. 1.9) and a low depth-to-water provide favourable conditions for thermal use in open-loop systems (Böttcher et al., 2019). The low depth-to-water, which decreases towards the north, commonly lies in depths from $4m$ (1^{st} qu.) to $10m$ (3^{rd} qu.) and, therefore, large parts of the groundwater body are exposed to seasonal temperature variations. Assuming 15 m as a hypothetical threshold for significant seasonal temperature oscillations, the groundwater in 91 % of the city's area is subject to those influences (Banks, 2012). In consequence, a periodical seasonal variation is present in most temperature measurements and complicates temporal or spatial interpretation.

6.2.2 Groundwater and infrastructure datasets

The following sections present the available groundwater and urban infrastructure datasets. In detail, depth profile and time-series measurements are distinguished to analyse specific vertical, temporal and lateral influences. Furthermore, the spatial datasets of the potential natural or anthropogenic thermal influences are introduced. A summary description of all datasets can be found in Table 6.1, and Figure 6.2 summarises the spatial distribution of the temperature measurements in the city.

6.2.2.1 Temperature depth profiles

From 2012 to 2017 in the months April to June, we measured groundwater temperatures in periodical field campaigns every metre below ground level (mbgl) in the water columns of

Table 6.1: SGE systems and numerical realization.

Spatial dataset	Count / Res.	Type	Dataset owner
Temperature depth profiles	752	Points	Chair of Hydrogeology (TUM)
Multi-annual temperature time series	71 / hourly to weekly	Points	Energy supplier / City of Munich
Saturated groundwater thickness	2 m	Raster grid	Bavarian Environmental Agency
Depth-to-water	2 m	Raster grid	Bavarian Environmental Agency
Darcy velocity	2 m	Raster grid	Bavarian Environmental Agency
Cooling systems (injection wells)	376	Points	Bavarian Environmental Agency
Heating systems (injection wells)	2341	Points	Bavarian Environmental Agency
Surface waters with groundwater-interaction	12	Polygons	OpenStreetMap contributors (2021)
Surface sealing	0.5 m	Raster grid	German Aerospace Centre
Built-up area	2 m	Raster grid	OpenStreetMap contributors (2021)
Sewer system sections	14783	Line segments	City of Munich
Heating grid sections	9663	Line segments	Energy supplier
Deep buildings	1286	Polygons	City of Munich
Metro stations	96	Polygons	City of Munich
Tunnel sections	127	Line segments	City of Munich

752 selected monitoring wells throughout the city (cf. Figure 6.2). In general, most of the approximately 16,000 measurements were taken at shallow depths of 2 to 20 mbgl. Although the measurements are available in a relatively short period from April to June, seasonal temperature fluctuations are already apparent. In Figure 6.3a, distributions of measurements for each month and metre below ground are displayed as boxplots. From April to June, the mean temperature at 2 mbgl already deviates by 3.7°C. The influence is still visible up to 6 mbgl. April is the most frequently measured month, with an average of 193 measurements, followed by June with 159 and May with 116.

6.2.2.2 Time series measurements

In Munich, 71 multi-annual time-series taken at a known constant depth are available (cf. Figure 6.2). The city's water authorities have recorded the longest 19 series at a 4-week frequency by hand measurements since 2009. Nine additional wells have been equipped with data loggers by the city's energy supplier in 2011, recording at a two-hour frequency since that time. The energy supplier extended this monitoring programme in 2014 with six data loggers, in 2015 with two, in 2016 with two, in 2017 with eight and in 2018 with another three. All data loggers that are maintained by the energy supplier were added at new sites and are equipped with NTC 30 temperature sensors. Furthermore, the city's water authorities started an extensive automated monitoring programme in 2018 by installing 20 additional data loggers at new sites that record hourly values with NTC 30 temperature sensors. The German Weather Service

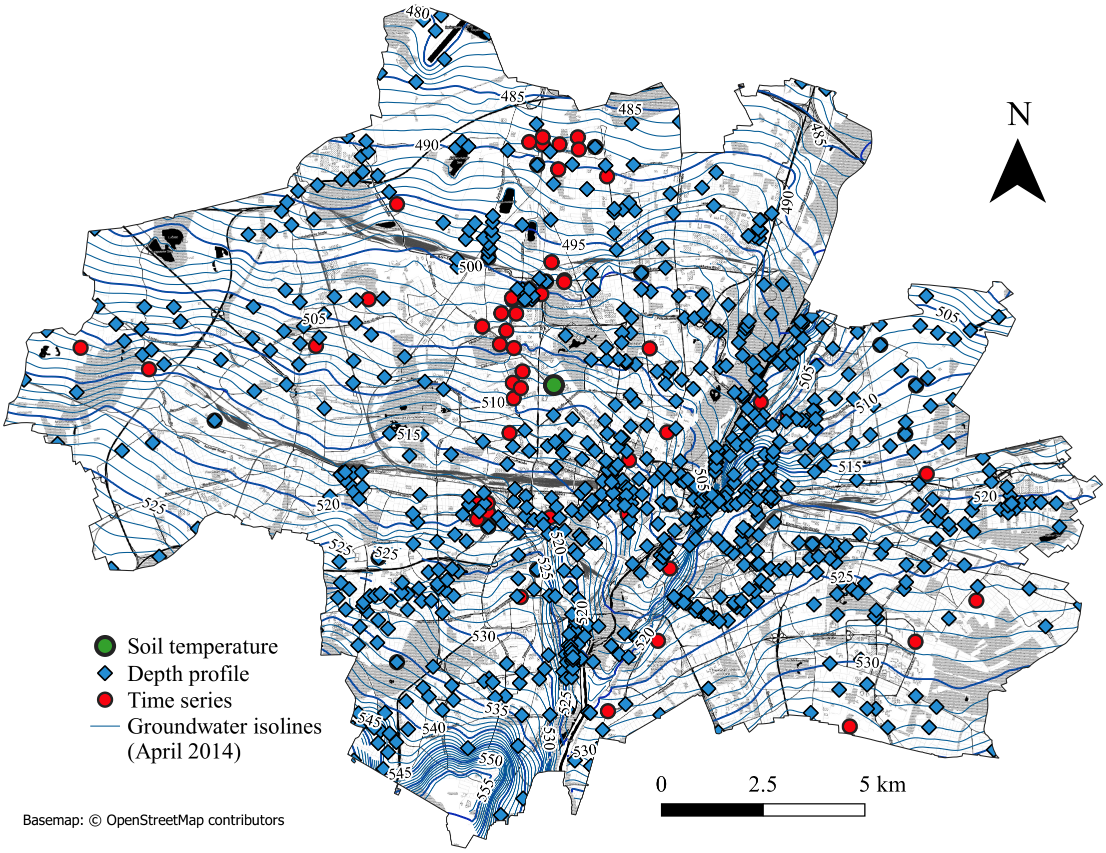


Figure 6.2: The spatial distribution of the different temperature datasets within the study area Munich and the interpolated groundwater isolines with hydraulic head labels from the reference date measurement in April 2014.

(DWD) also maintains one soil temperature monitoring station in the city, which records at five depths of up to 1 m on an hourly basis with PT 100 temperature sensors, since July 1997. Since the measurements are not conducted within an integrated monitoring network, the selection of sites does not follow a common strategy. A situation that is often found in large cities.

6.2.2.3 Spatial hydrogeological datasets

In the Munich Gravel Plain, high-resolution spatial datasets of hydrogeological properties provide the opportunity to analyse their influences on groundwater temperature in detail. Within a four-year project, funded by the Bavarian Environmental Agency (LfU), the Chair of Hydrogeology elaborated the surface of the quaternary aquifer basis of the entire Munich Gravel Plain based on the interpretation of over 48,000 borehole logs. In addition, an extensive reference date measurement was carried out in April 2014, capturing the hydraulic dynamics during mean low groundwater conditions (Böttcher et al., 2019; Albarrán-Ordás and Zosseder,

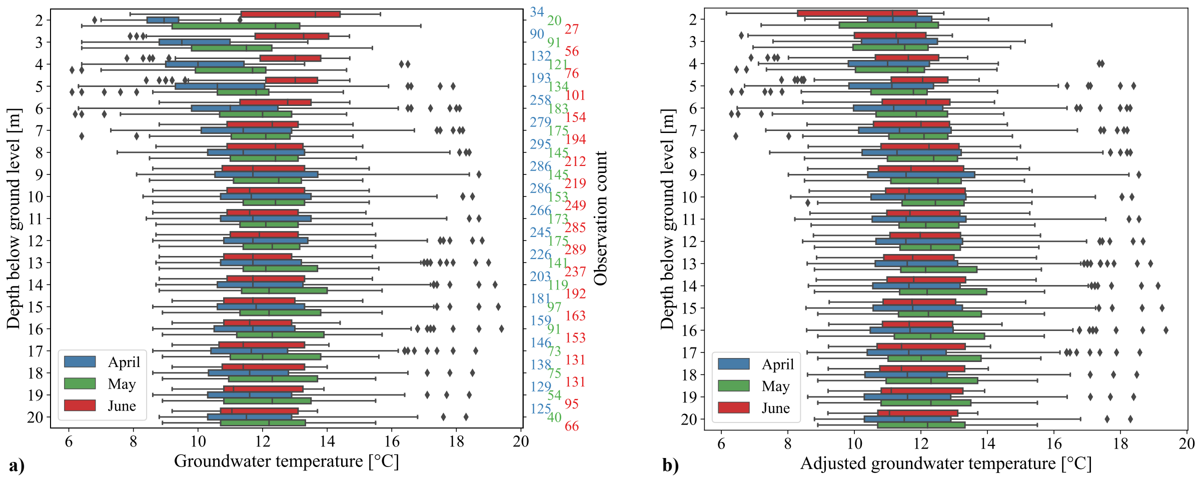


Figure 6.3: Monthly distribution of a) the initial groundwater temperatures and b) the seasonally corrected temperatures that are referenced to the 12th of May in a one-metre vertical resolution displayed as boxplots with an interquartile range (IQR) of 50% and whiskers with 1.5*IQR. The right-hand y-axis of a) shows the observation count per depth below ground in the colour of the respective month.

2020). The conditions represent an equilibrated and robust flow field that reflects the common hydraulic situation throughout the year. A comparison with other available groundwater table maps from the past, including datasets with less sample points and thus, lower accuracy, showed only minor local changes in the groundwater flow field. Hence, the dataset has a high general validity and only minor errors are introduced in derived datasets. Throughout the entire Munich Gravel Plain, over 6,000 hydraulic head measurements were used to interpolate a map of the groundwater table by variogram analysis and block kriging (Böttcher et al., 2019; Albarrán-Ordás and Zosseder, 2020). The saturated thickness of the aquifer was derived by subtracting the surface of the aquifer basis from the interpolated hydraulic head (cf. Figure 6.1a and Figure 6.2). The hydraulic head is further used to calculate the hydraulic gradient, and with the 2-m digital elevation model, the depth-to-water is computed (cf. Figure 6.1d). During the 2014 field campaign, groundwater temperatures were measured one metre below groundwater level and one metre above total depth in around 1,800 observation wells, and a temperature distribution map was interpolated by block kriging for the entire gravel plain (cf. Figure 6.1b).

The Darcy velocity was calculated by multiplying the interpolated hydraulic conductivity map of Theel et al. (2020) with the hydraulic gradient and therefore, the Darcy velocity incorporates the uncertainties of those two dataset (cf. Figure 6.1c and Figure 6.2). As stated above, we assume minor errors from hydraulic gradients. The hydraulic conductivity, however, can be heterogeneous at small scale and the distribution of analysed pumping tests is still not sufficient to capture this heterogeneity (Theel et al., 2020). The used 542 pumping tests represent the entire data currently available and thus, this residual uncertainty has to be taken into account in further interpretations.

6.2.2.4 Spatial infrastructure dataset

In the present study, surface sealing is used as the primary dataset to reflect urbanisation and anthropogenic land use (cf. Figure 6.1f). The German Aerospace Centre (DLR) conducted the mapping with a mosaic of eight-band image data at a spatial resolution of 2 m from the WorldView-2 sensor, recorded on the 12th of July and the 2nd of October 2011 (Leichtle et al., 2018). The binary classification of the multispectral satellite imagery is performed by a semi-automatic object-based approach, which integrates auxiliary vector datasets, like building boundaries from the German Official Topographic Cartographic Information System (ATKIS), on different evaluation levels (Wurm et al., 2011).

In addition to the spatial grid information, also vector datasets of potential anthropogenic heat sources are evaluated. As an extension to the analysis of surface sealing, we include building outlines (OpenStreetMap:contributors, 2021). Furthermore, we considered deep building basements that reach into the groundwater body, metro stations and surface waters separately as polygon features. As line features, the district heating grid, the sewer system and tunnels are included in the analyses. Finally, thermal uses for heating and cooling purposes are characterised as point features. These datasets were provided by the City of Munich and the Munich Public Services SWM GmbH (cf. Table 6.1).

6.2.3 Correction of depth profile temperatures

Surface temperature oscillations attenuate naturally in the ground, while the lag of the signal increases and the amplitude decreases with depth (Banks, 2009a). Diurnal variations only reach several decimetres into the ground, whereas the boxplots in Figure 6.3a already show that substantial seasonal variations penetrate a few metres into the ground until the signal dissipates (Van Wijk and de Vries, 1963). As outlined in the introduction, this variation impedes identifying additional anthropogenic or natural influences on the ground temperature. Therefore, the following section covers the developed approach of estimating the seasonal variation present in the study area. The depth-depended seasonal oscillation is further used to adjust the multitemporal depth profile dataset to one reference date. The adjustment enables the comparison of temperatures that had originally been measured at different times within the zone of seasonal fluctuation. As a result, the adjusted temperatures can be used in regression analyses to reveal the influence of anthropogenic or natural heat sources (cf. Table 6.1).

The calculation of the typical seasonal variation is performed by estimating the thermal diffusivity through the extraction of amplitude and phase from the time-series data presented in

Section 6.2.2.2. Initially, an additive decomposition into trend, seasonal and random components was carried out to calculate the amplitude of the seasonal oscillation (Kendall et al., 1983). First, the trend component was determined using a moving average as a low-pass filter with a symmetric window and equal weights. Then, the trend is removed from the time series, and the seasonal component is computed by averaging, for each time unit, over all periods. Finally, the error component is determined by removing the trend and the seasonal component from the original time series.

The seasonal components extracted from the differently deep time series, as shown in Figure 6.4, (cf. Section 6.2.2.2) were further used to compute the cross-correlation between the shallowest time series and the deeper groundwater temperature time series (Venables and Ripley, 2002). As a result, the maximum cross-correlation determines the time lag between the respective groundwater temperature oscillations and the shallowest temperature oscillation, i.e. the ground temperature 1 m below surface. The amplitude and time lag data derived is then used to estimate the thermal diffusivity.

To describe an average thermal response in the groundwater, we assume no vertical fluid flow. Hence, the vertical heat transport is considered entirely conductive, and we assume that the seasonal influence is the only oscillation in the monitored depths (Goto, 2005; Hatch et al., 2006; Keery et al., 2007; Molina-Giraldo et al., 2011). Therefore, in a semi-infinite solid where the surface temperature is a harmonic function in time, the temperature fluctuation in time and depth $\Delta T(t,z)$ can be calculated by the initial amplitude at the surface (A), the thermal diffusivity (κ), the relative phase (θ) and the period of the oscillation (P) with Stallman (1965); Carslow et al. (1986)

$$\Delta T(t,z) = Ae^{-z\sqrt{\frac{\pi}{\kappa P}}} cos\left(\frac{2\pi t}{P} - \theta - z\sqrt{\frac{\pi}{\kappa P}}\right) \tag{6.1}$$

Thus, the damping of the amplitude (A_D) at a specific depth (z) can be calculated by an annual period of 365 days with

$$A_D = Ae^{-z\sqrt{\frac{\pi}{\kappa P}}} \tag{6.2}$$

The progressive lag, as the relative phase difference ($\Delta\theta$) between a pair of temperature time series at different depths, is given by

$$\Delta\theta = \theta - z\sqrt{\frac{\pi}{\kappa P}} \tag{6.3}$$

which can be converted to a time lag (Δt) with

$$\Delta t = \frac{P}{2\pi}\Delta\theta \tag{6.4}$$

In consequence, the thermal diffusivity can be independently estimated, either from equation (6.2) or equation (6.3) (Thomson, 1861). This is done by fitting the equations through a linear regression analysis using the extracted amplitude and time lag data of the recorded temperature time series with the specific measurement depths. The weighted arithmetic mean thermal diffusivity of the two estimates from the time lag and amplitude regression is then inserted in equation (6.1) for a time and depth-dependent calculation of the mean temperature change due to seasonal oscillation in the study area. To derive the weighted mean, weights are given by the reciprocal of the regression coefficient's variance.

Furthermore, equation (6.1) can be applied to the multi-temporal depth profile dataset to derive the seasonal temperature difference $\Delta T(t_0,z)$ originating from different measurement dates and depths. Thus, a corrected temperature (T_0) is calculated by adjusting all the original temperature values (T) to a single measurement time through

$$T_0 = T + \Delta T(t_0,z) - \Delta T(t,z) \tag{6.5}$$

With this, the difference of the seasonal temperature share (ΔT) at the desired time (t_0) and the actual measurement time (t) is calculated. After subtracting the seasonal share from the temperature measurements, the adjusted temperature dataset is used to evaluate the driving and diminishing factors on the SSUHI.

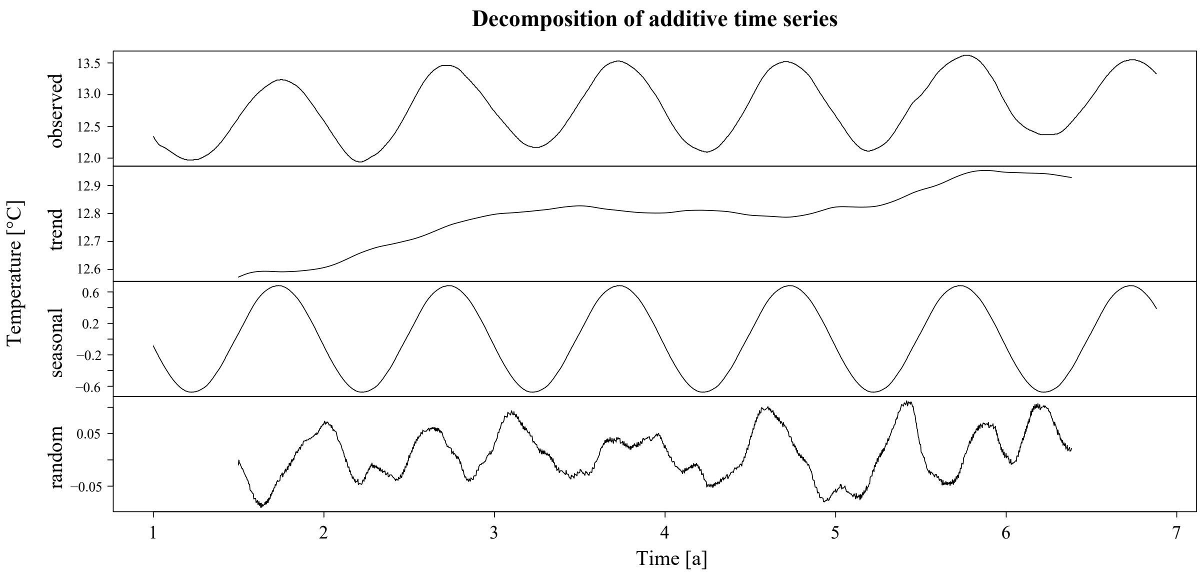


Figure 6.4: Exemplary decomposition of a groundwater temperature time series with a seven-year duration and negligible residual random noise used to extract the seasonal component.

6.2.4 Statistical analysis of thermal influences on the groundwater

This section describes the procedures that we apply to account for the structurally different impact of several factors. Following Visser et al. (2020), we distinguish between large-scale factors and local-scale factors. For large-scale factors, i.e., the raster grid datasets summarised in Table 6.1, we initially determine the area that shows the strongest correlation with the measured groundwater temperatures. Since the thermal influence on a well arises primarily from up-gradient in an advection-dominated aquifer, it is relevant to query the area where dispersive effects have not yet dispelled the dependency between the respective spatial factor and the groundwater temperature. Hence, we derive the maximum Pearson correlation by varying the extent of the up-gradient area in which the spatial factor is aggregated. Specifically, the mean value within an up-gradient directed triangle is computed for all well locations, as shown in Figure 6.5a. This aggregation is repeated with a combination of opening angles at the well and up-gradient triangle lengths. Subsequently, the correlation of the aggregated factor values is conducted with the seasonally adjusted mean temperature per depth profile. The resulting correlation matrix for surface sealing is visualised in Figure 6.5b as an example. The correlation reaches a maximum for triangles with a 60° opening angle and a length of 900m. As a result, the strongest correlation of every large-scale factor is determined in a data-driven and exploratory manner. For the ratio of built-up area, the maximum correlation is present for a triangle with a 90°angle and a length of 1000m. The angle and triangle length result for saturated aquifer thickness is 45°/1000m, for Darcy velocity 120°/1400 m and for depth-to-water 30°/1400m.

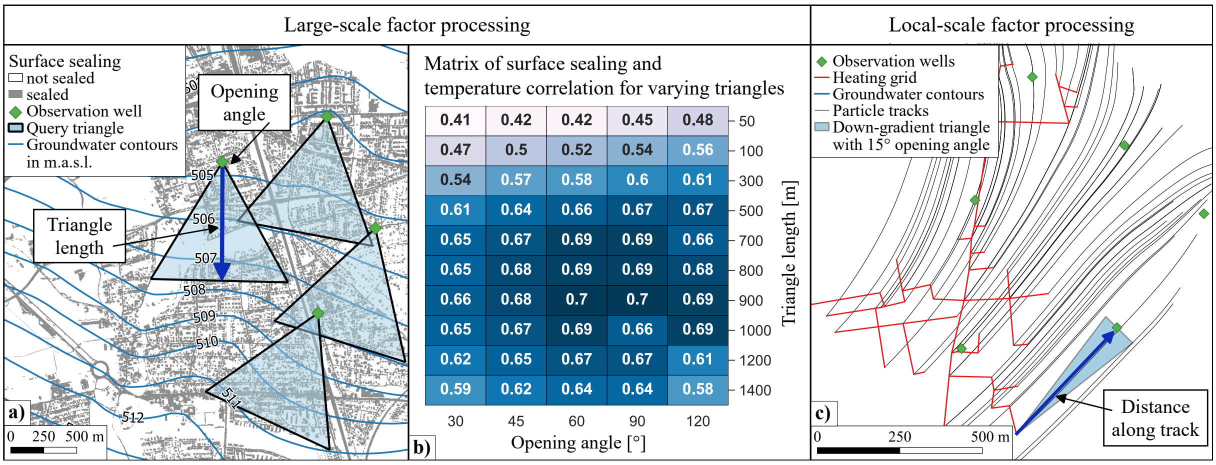


Figure 6.5: a) Spatial evaluation of large-scale factors, i.e. raster grid data, with a calculation of the mean for different triangle sizes, b) resulting correlation matrix to identify the triangle size with the maximum correlation between the temperatures and the mean values with high correlation in dark blue and low correlation in light blue and c) particle track calculation for local-scale factors, i.e. vector data, to acquire the upstream distance between an observation well and a vector feature within a hypothetical plume of 15°opening angle.

The large triangle sizes for hydrogeological factors improve the robustness of the aggregated mean values, because generally the underlying values, like Darcy velocity, show less temporal and spatial variance in larger areas.

Local-scale influences, which are represented as geometrical features, behave differently (see Table 6.1). They potentially induce a thermal anomaly that diminishes while propagating down-gradient. Thus, we derive the distance from a local feature to a down-gradient observation well along the path of advection in the flow field (Konikow and Bredehoeft, 1984). In detail, we apply the implementation by Tauxe (1994) that allows the computation of a particle track from a point source by using the grid data of Darcy velocity and groundwater flow direction. In addition, we consider transversal dispersion in a simplified manner by excluding down-gradient connections if the well lies outside the study area's typical opening angle of a potential thermal plume of 15°(see Figure 6.5c). Through this procedure, each observation well is attributed with its distances to all up-gradient local-scale factors, if present.

Finally, the influence of all factors is compared by estimating the standardised (beta-)coefficients in multiple linear regressions (Greenland et al., 1991; Schielzeth, 2010). In the following analyses of this study, we use beta-coefficients as an indicator for the comparative influence of a predictor with respect to the remaining predictors. For an estimation of beta-coefficients, the underlying data of the predictor variables was standardised by computing the z-score before performing the regression analysis (Menard, 2004; Everitt and Hothorn, 2011). As dependent variable, the adjusted mean temperature per depth profile is used for an initial evaluation of the overall influence and significance among all predictors (cf. Figure 6.3b). Subsequently, only the dominant and significant predictors are used for computing the beta-coefficients each metre below ground from 3 to 20*m* to reveal the depth-dependent change of influences.

Furthermore, the dominant large-scale factors are used to derive a map showing the aggregated heating and cooling influence on the groundwater by a specifically calculated thermal exposure score. Therefore, the beta-coefficients at the respective average depth of the groundwater body are used to solve the regression function with the z-score of the predictor's grid values. The resulting values are then normalised from -1 to 1 and offer a spatial visualisation of the comparative impact on the aquifer's thermal conditions. As a result, negative scores indicate areas where the urban and natural conditions have a cooling potential and positive values highlight areas where the groundwater likely to be heated by the assessed influences.

6.3 Results

In the following, results are presented in two sections. The first section comprises the seasonal variability analysis of the time-series data, the estimation of the weighted mean thermal diffusivity and the seasonal correction of the multi-temporal depth profile measurements to one reference date. The second section contains the comparative analysis of the potential influences of large and local-scale factors on groundwater temperature, the evaluation of vertical changes in the effect size of dominant influences and finally, the spatial assessment of the dominant city-wide influences, which is displayed in a thermal exposure map of the study area.

6.3.1 Seasonal temperature influences

Initially, the additive decomposition and cross-correlation of the seasonal component is conducted for all 71 groundwater temperature time series (cf. Figure 6.4). With this, the amplitude of the seasonal variation and the time lag with respect to the shallowest measurement depth is obtained (cf. Section 6.2.4). The previous assumption of seasonality being the only relevant oscillation is proven by a constantly low residual variation in the random component. No diurnal or other substantial oscillations of lower frequency have been observed. The mean variance of the random component in the entire dataset is 0.07°C, corresponding to only 4.3% of the mean seasonal variation. In addition, we reviewed, if general trends in the amplitudes are present. A negative trend in amplitudes would generally result in a positive correlation between seasonal and random component in the first half of the time series and a negative correlation in the second half. Four time series with a negative amplitude and five time series with a positive amplitude trend were identified. However, the identified time series are no influential outliers in the regression analyses and thus, do not negatively affect the thermal diffusivity estimation. Figure 6.6a displays the derived seasonal time lags at the respective measurement depth. Subsequently, the data is used to fit equation (6.3) with the origin at one metre below ground, which results in a thermal diffusivity of $1.6 \times 10^{-6} m^2 s^{-1}$ with a standard error of $1 \times 10^{-7} m^2 s^{-1}$. The linear function fitted shows that a time lag of 14.4 days for every metre deeper below ground level can be expected as a mean value within the study area. As described in Section 6.2.4, the procedure of thermal diffusivity estimation is repeated using the seasonal amplitudes. Figure 6.6b shows the measurement depth against the seasonal amplitude for the same time series data. Here, equation (6.2) is used to fit the two regression coefficients, which leads to an estimated thermal diffusivity of $1.1 \times 10^{-6} m^2 s^{-1}$ with a standard error of $1 \times 10^{-7} m^2 s^{-1}$.

From both thermal diffusivity estimations, the resulting weighted mean of $1.2 \times 10^{-6} m^2 s^{-1}$ with a standard error of $1 \times 10^{-7} m^2 s^{-1}$ is used in equation (6.1) to calculate the typical seasonal temperature oscillation of the study area from 0 mbgl to 20 mbgl. The mean temperature of 12.2°C from the 1^{st} of August 1997 to the 1^{st} of August 2020 of the continuous measurements 1 mbgl of the DWD is added to obtain the monthly variation of one year.

With equation (6.5), all the depth-oriented temperatures are seasonally corrected by computing the temperature difference from the actual measurement date to the mean measurement date, i.e. the 12^{th} of May, and adding this change to the initially measured value. In comparison with Figure 6.3a, Figure 6.3b displays the achieved absence of seasonal variation, especially

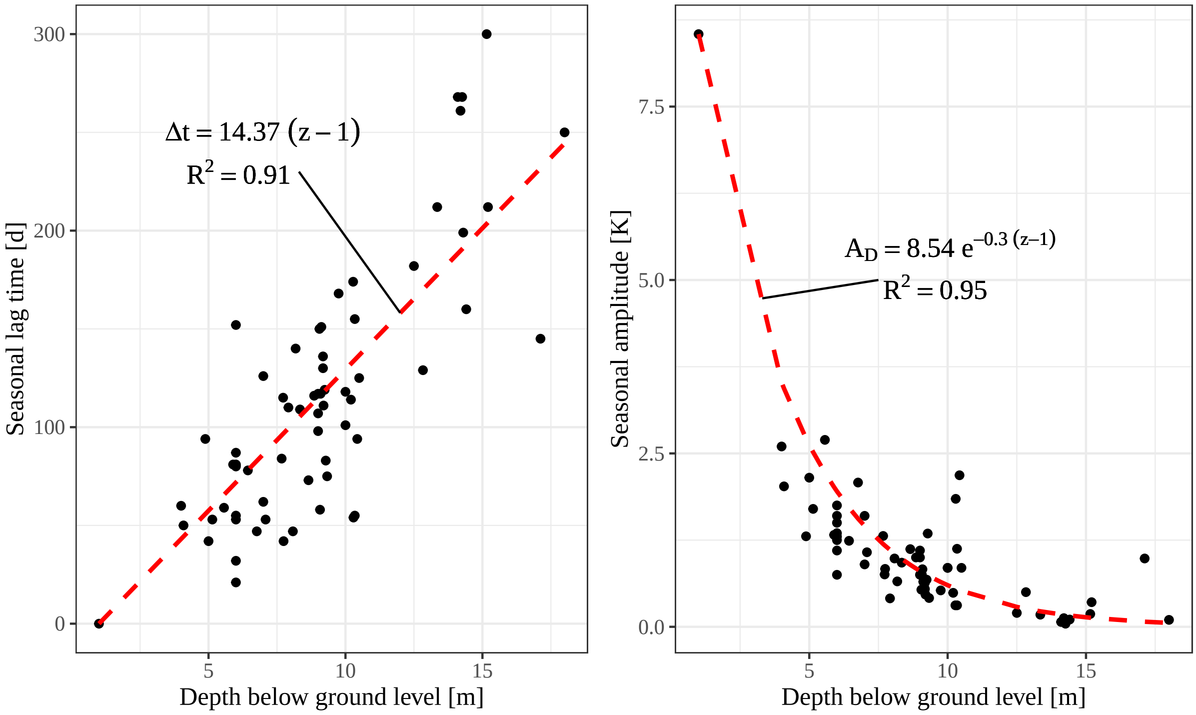


Figure 6.6: a) Lag time and b) seasonal amplitude against depth below ground, both with the estimated regression function (red), as well as the formula and R^2.

observable from the mean values in the boxplots of the upper five metres. In detail, the variance two metres below the surface was reduced from 6.6°C to 3.6°C. Thus, the direct statistical analysis of measurements taken at different times is possible because the bias from changing seasonal conditions is marginalised. In the following, the adjusted temperature-depth profiles are used in multiple linear regression analysis to identify the dominant increasing and decreasing effects on the SSUHI.

6.3.2 Anthropogenic and natural influences on Munich's groundwater temperature

Following the approach described in Section 2.5, the correlations between groundwater temperature and the influential factors and cross-correlations among influential factors are determined. The resulting correlation coefficients between temperature and the respective factors are given in the first row of the matrix in Figure 6.7. We observe equally strong positive correlations for sealed surfaces and built-up areas with high groundwater temperatures. They are followed by weaker positive correlations of the district heating grid and the Darcy velocity. In contrast, a weak negative correlation can be observed for the depth-to-water and the strongest negative correlation for saturated thickness. In general, the correlations of the factors

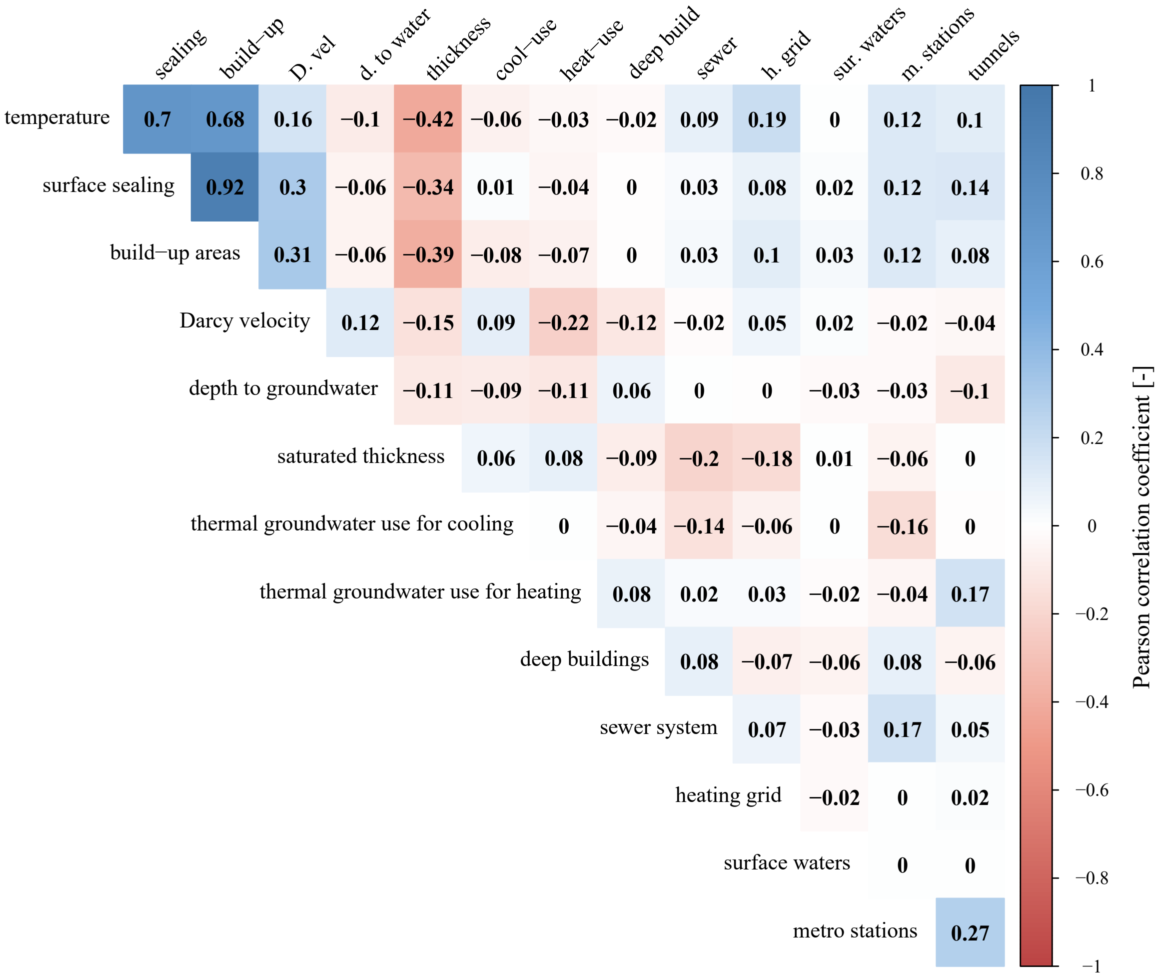


Figure 6.7: Matrix of (Pearson-) correlations between predictors and the groundwater temperature in the first row and predictor correlations with colour coded correlation coefficients.

with the temperature already give an initial indication of dependencies. However, only one factor at a time is considered while the superposition of all other factors are omitted. This can lead to significant biases, as can be observed for the Darcy velocity. The hypothesis is that dispersion increases with increasing flow velocity and thermal anomalies dissipate more quickly. Therefore, one would expect a cooling influence to be more likely than a heating one. In the specific case of Darcy velocity, however, we also see a positive correlation with surface sealing and, simultaneously, a negative correlation with aquifer thickness. Since surface sealing has the strongest positive and aquifer thickness the strongest negative correlation with the temperature, the correlation of the Darcy velocity will be biased towards positive values. This result

Table 6.2: Regression summary of the beta-coefficient estimation for all predictor variables with t-test and respective p-value.

Regression coefficient	Estimate	t value	Pr $(> \|t\|)$
Intercept	12.03	850.1	$< 2e-16$
Saturated groundwater thickness	-0.33	-20.0	$< 2e-16$
Depth-to-water	-0.13	-8.6	$< 2e-16$
Darcy velocity	-0.11	-6.9	$< 2e-16$
Cooling systems (injection wells)	-0.07	-4.6	$5.1e-06$
Heating systems (injection wells)	-0.02	-1.2	0.23
Surface waters with groundwater interaction	-0.02	-1.3	0.21
Surface sealing	0.93	24.9	$< 2e-16$
Built-up area	0.17	4.4	$1.1e-05$
Sewer system sections	0.03	1.8	0.07
Heating grid sections	0.17	11.8	$< 2e-16$
Deep buildings	-0.07	-4.6	$4.4e-06$
Metro stations	0.03	2.5	0.01
Tunnel sections	-0.001	-0.1	0.93

shows that a comparative analysis in a multiple regression is necessary to further reveal the heating and cooling effects on the groundwater without considerable bias.

Apart from the correlation with groundwater temperature, Figure 6.7 shows the cross-correlation among all predictors. A very large positive correlation of surface sealing with built-up area indicates the presence of multicollinearity. The magnitude of multicollinearity in predictors of a multiple regression can be measured by the variance inflation factor (VIF) (Fox and Monette, 1992). The high VIFs of 7.0 for surface sealing and 7.4 for built-up area confirm the high degree of collinear relationship. Since the surface sealing already includes built-up areas, as well as the other sealing structures, it serves as a cumulative factor for urbanisation, which is suitable for city-scale analyses. It is assumed that the built-up area is already sufficiently represented by the surface sealing. Consequently, the less influential built-up area is removed from the further depth-oriented regression analysis. The correlation matrix further shows the absence of a high correlation between the remaining predictors (see Figure 6.7). Furthermore, a low correlation among the local-scale predictors can be observed, due to the lack of spatial coincidence. As an example, there is no depth profile in the dataset where the district heating grid and a surface water is simultaneously up-gradient of a measurement location. This was anticipated, since the surface waters with groundwater interaction lie exclusively near the northern border of the city where no district heating grid exists. Thus, the results reflect the spatial distribution of the local-scale factors, which does not negatively affect the regression results.

Table 6.2 shows the results of the initial multiple linear regression analysis of all large and local-scale factors studied. In detail, the z-scores are used with the mean temperature per depth

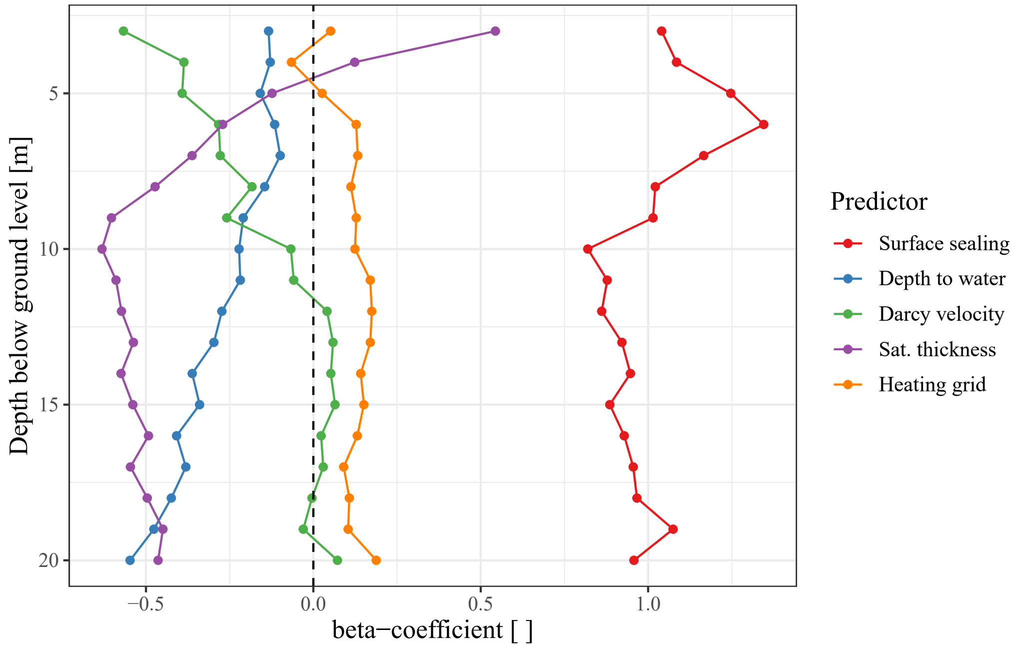


Figure 6.8: Change of beta-coefficients against depth below ground for the dominant predictors.

profile to obtain the beta-coefficients, which allow us to compare influences and select dominant predictors for the depth-oriented analysis (cf. Section 6.2.4). There are already predictors within the dataset which cannot reach statistical significance, i.e. heating uses, surface waters and tunnels. In addition, sewers and metro stations exhibit a low significance. Among the significant predictors, surface sealing in particular shows the strongest positive influence, and saturated thickness the strongest negative one. They are followed by the district heating grid, built-up area, Darcy velocity and depth-to-water with considerable influences. As a result, the remaining predictors with minimal influence, i.e., cooling uses and deep buildings, sewers and metro stations are excluded from further depth-oriented analysis.

Figure 6.8 displays the results of the depth-oriented multiple regression analysis with the five selected dominant factors. The x-axis shows the change of influence, i.e. the beta-coefficient, against the depth below ground for each factor. The depth of 2 mbgl is omitted, due to a low observation count (cf. Figure 6.3a). First, it is noticeable that substantial vertical trends are only observable for cooling factors, whereas the influence of the surface sealing and the heating grid is relatively constant (cf. Figure 6.8). The surface sealing maintains its very high driving influence on the groundwater temperature with the highest values around 5 mbgl to 7 mbgl. The heating grid shows a low but relatively continuous positive influence. In contrast, the cooling effect of depth-to-water is steadily increasing towards deeper levels and even surpasses the saturated thickness below 19 mbgl as dominant negative influence. For saturated thickness, the cooling effect increases until a depth of 10 mbgl and remains on a constant high negative influence in greater depths. The opposite behaviour can be observed for Darcy velocity. Its cooling effect steadily declines until it remains at around zero below depths of 10 mbgl. For all depth-dependent regressions, the beta-coefficients are statistically significant and the mean R^2 is 0.53 for depths above 10 mbgl, whereas it reaches 0.67 from 10 mbgl and below.

For a spatial visualisation of predictor influences, the dominant large-scale factors, i.e., surface sealing, depth-to-water, Darcy velocity and saturated thickness, are included in the thermal exposure score calculation. Figure 6.9 presents the resulting grid, which indicates the exposure of the aquifer to the SSUHI (cf. Section 6.2.4). A positive score indicates that the dominant drivers prevail and the groundwater is subject to anthropogenic heating from surface sealing, whereas a negative score shows the dominance of cooling conditions from hydrogeological influences. The thermal exposure score has a Pearson correlation of 0.64 with the interpolated groundwater temperature. This already indicates how dominant large-scale factors contribute to the SSUHI and shows that local-scale factors are less significant on a city-wide scale. The temperatures displayed in Figure 6.9 were measured one metre below groundwater level in

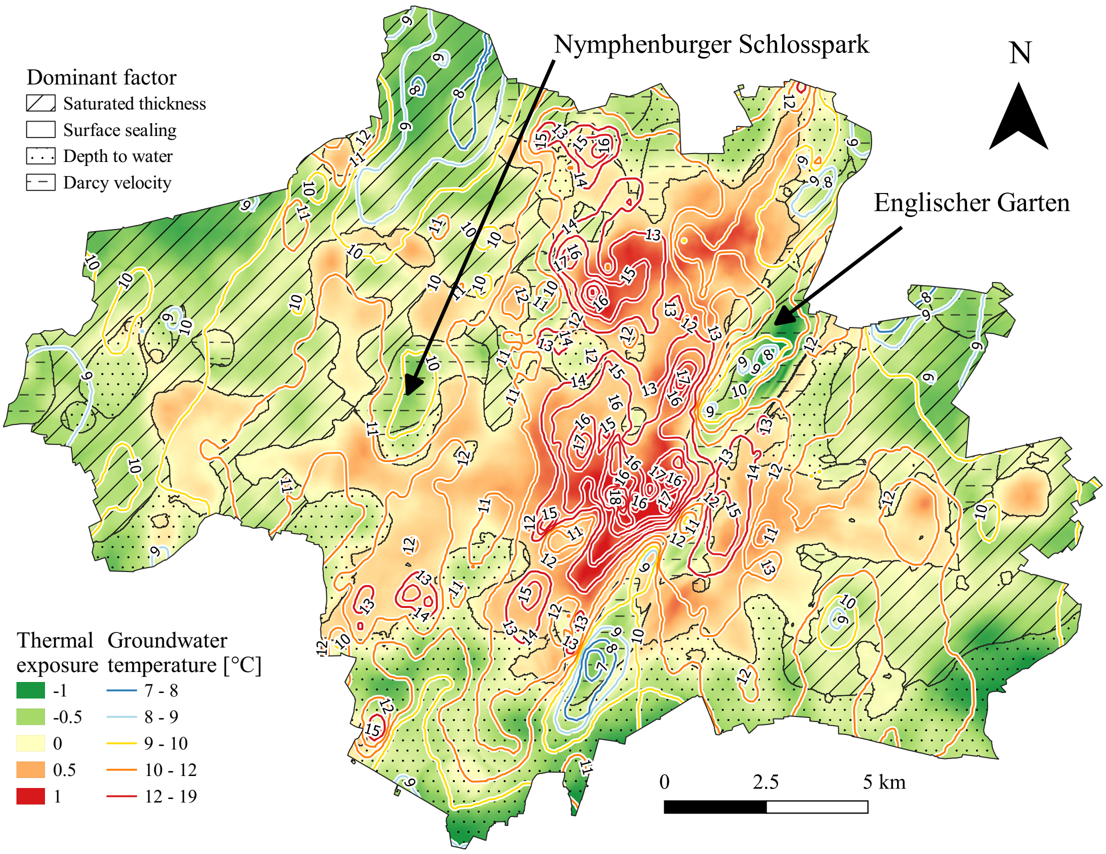


Figure 6.9: Map of the thermal exposure score with an overlay pattern indicating the dominant factor in the score calculation and the contour lines of groundwater temperature interpolated from a reference date measurement in April 2014.

April 2014 (cf. Section 6.2.2). Finally, the overlay pattern highlights the locally dominant factor resulting from the maximum product of the absolute beta-coefficient and z-score among the four predictors.

6.4 Discussion

The study developed a workflow based on exploratory data analysis for the evaluation of influences on the SSUHI in shallow aquifers. We applied a passive heat tracing procedure to estimate the weighted mean thermal diffusivity of the study area and successfully adjusted multi-temporal temperature measurements to a common seasonal state of a reference date. The large number of measurements analysed revealed that the sealing of the ground surface and built-up areas are the dominant drivers of anthropogenic groundwater warming in Munich. In addition, we showed that local-scale factors, like thermal groundwater uses, surface waters and underground structures do not have a significant influence on a city-wide scale. Moreover, we statistically elaborated how the magnitude of dominant influence changes with depth and thereby highlight the importance of the natural influence of saturated thickness, the Darcy velocity and the depth-to-water as major decreasing factors for groundwater warming. Finally, we calculated a thermal exposure score to display how the combined influence of large-scale influences matches the spatial groundwater temperature distribution and can therefore explain the SSUHI effect.

6.4.1 Discussion of the seasonal temperature influences

In the first step of the process, the classic additive approach proved its suitability by decomposing the 71 time series with minor residual variance in the random component. For this reason, the seasonal components derived serve as a resilient data basis for an extraction of time lag and amplitude. In addition, the dataset acquired covers the entire zone of seasonal fluctuation with a sufficient measurement density. The time-series dataset only lacks information from 1 mbgl to 4 mbgl, caused by the distribution of depth-to-water, as well as the common practice of installing temperature and pressure sensors near the bottom of observation wells. However, we could not observe a negative effect on the regression analyses. As verification, we calculated the Cook's distance, which is a measure of the influence of an observation on the regression result and takes leverage and residual into account (Cook, 1977). Based on its low Cook's distance (< 0.5), the measurement at 1 mbgl cannot be identified as an influential outlier, which indicates that the shallow area is already sufficiently represented. This observation is valid for both regression analyses (see Figure 6.6).

In addition, it can be observed from Figure 6.6 that the lag time and amplitude data has a residual variation, which cannot be explained by the fit of the regression equations. With the regression analysis, we derive the mean thermal diffusivity in the study area. Therefore, the residual variation originates mainly from different thermal diffusivities at the specific measurement sites. Since we assume the simplifications mentioned in Section 6.2.4, factors like a heterogeneous geology, the thickness of the unsaturated zone or the influence of other seasonal heat sources or sinks are not considered.

Furthermore, the differently high standard errors of the regression coefficients suggest that the estimated thermal diffusivities should be weighted according to their errors. Thus, we conducted the seasonal correction with the weighted mean thermal diffusivity. In comparison with the German VDI 4640-1, which states ranges of thermal conductivity and volumetric heat capacity, the resulting thermal diffusivity lies 65% above the typical characteristic value for saturated gravel and 29% above saturated sand. However, the thermal conductivity can vary considerably, with changing mineral composition and a total range of thermal diffusivity for saturated sand being given of between $0.59 \times 10^{-6} m^2 s^{-1}$ and $2.3 \times 10^{-6} m^2 s^{-1}$ (VDI, 4640). Therefore, the resulting averaged thermal diffusivity for the saturated sandy gravel of Munich ($1.24 \times 10^{-6} m^2 s^{-1}$) lies within a plausible range, although it is slightly elevated in comparison with typical characteristic values. Since Munich has a humid climate with a downward flow of infiltrated water in the vadose zone, a steady contribution by advective heat transport influences the groundwater when recharged. The enhanced heat transport as well as further convection in the groundwater body is not accounted for in the applied heat tracing method and elevated estimates are thus plausible. However, this deviation does not impair the statistical application in the correction procedure within the scope of this study, as the result integrates those effects through the least squares fit of the regression analysis (Kendall et al., 1983).

The same limitation is valid for the seasonal correction itself. Due to site specific influences, it may only be used in a statistical manner with a sufficient population size and not for adjusting individual temperature profiles. However, the statistical application showed that the seasonal effect has disappeared, which can be observed from comparing Figure 6.3a and Figure 6.3b. After the adjustment, the temperatures of all shallow depth levels show the same variance as the temperatures measured below 10 mbgl, i.e., approximately 3°C. Thus, any bias in the regression analyses from different seasonal states has been successfully minimised.

6.4.2 Discussion of the anthropogenic and natural influences

Prior to the regression analyses, the definition of the maximum influential area with triangular shapes revealed how spatial parameters differently affect the groundwater temperature. First, it can be stated that a single point value at the location of the measurement is generally not optimal for studying the dependency of a large-scale factor on groundwater temperature (cf. Figure 6.5b). Consequently, in aquifers dominated by advective heat transport, any investigation that considers an up-gradient region with respect to the local groundwater flow direction will lead to stronger correlations because it reflects the advective transport processes. The possible gain in correlation strength will depend on the spatial variability of the factor. Since the hydrogeological parameters show less spatial heterogeneity than surface sealing and built-up area, the correlation coefficient also varies less (cf. Figure 6.2). However, it can be concluded that the chosen procedure of considering the predictor values with the maximum correlation greatly affected the estimation and significance of regression coefficients and, therefore, improved the regression analyses.

Our findings in the initial comparative regression analysis are mostly in line with the interpretations of Dohr and Gruban (1999) and Zosseder et al. (2015). Similar to many international SSUHI studies, we confirmed building density and surface sealing as major driving factors of subsurface warming in Munich (Taniguchi et al., 2005, 2009; Yalcin and Yetemen, 2009; Epting and Huggenberger, 2013; Lokoshchenko and Korneva, 2015; Bucci et al., 2017; Marschalko et al., 2018; Visser et al., 2020). By using a novel surface sealing dataset, we were able to highlight the importance of green areas within the city to counteract the SSUHI effect. Most notably, this can be observed for the Englischer Garten, which lies Northeast of the city centre (cf. Figure 6.9). In addition, surface sealing as a cumulative parameter for urban land use was superior to building footprints for the explanation of groundwater warming. Therefore, our results are consistent with the findings by Benz et al. (2018) that in the absence of underground structures and basements, asphalt-covered land causes heat fluxes of a similar magnitude to buildings.

Furthermore, we proved the importance of hydrogeological factors for the temperature development of urban groundwater. As initially noticed by Zosseder et al. (2015), areas with low saturated thickness can have naturally increased groundwater temperatures and may so potentially mask anthropogenic influences. A groundwater body with a higher saturated thickness can absorb more heat before the temperature increases, due to the larger water volume and the larger amount of advective heat transport. This leads to increased dispersion and consequently to the dissipation of higher temperatures. For that reason, our results indicate that advective heat transport constitutes the most important natural cause of higher or lower temperatures. Furthermore, the magnitude of advective heat transport is governed by the Darcy velocity. Hence, its influence is consistent with the anticipated cooling impact and confirms the plausibility and robustness of the regression estimation. The depth-to-water serves instead as an insulator between the surface and the groundwater body, due to the reduced thermal conductivity of the variably saturated zone with increasing air content. Thus, the regression estimate corresponds to its expected cooling influence, while the weak correlation with other factors verifies the absence of a negative spatial bias from the fact that the depth-to-water steadily decreases towards the north (cf. Figure 6.1d). In conclusion, we emphasise that the natural conditions must be accounted for in future thermal evaluations of urban aquifers. Otherwise, naturally cooled or heated areas will not be identified, climate-driven temperature changes will not be detected or perhaps wrongly classified as anthropogenic influenced (Epting and Huggenberger, 2013).

The comparative regression analysis of all predictors did not reveal a significant influence of thermal groundwater use for heating nor a positive influence for cooling, which is in line with (Dohr and Gruban, 1999). A warming influence of cooling systems and a cooling influence of heating systems would have been anticipated through direct advective inflow of thermally altered water (Stauffer et al., 2014). In part, the missing evidence for the impact of thermal uses can be explained by the measurement time. From April to June, the heating period is usually over and the domestic cooling period has - in most cases - not yet started. Therefore, thermal anomalies from small and medium-sized uses with a seasonal load profile could be already dissipated. Furthermore, larger cooling systems with relatively constant loads that might have a considerable local impact could not establish a warming influence on a city-wide scale. The small negative beta-coefficient for cooling systems can result from random residual noise in the temperature measurements which was attributed to the variation of this factor and can, therefore not be linked to a causal reason. However, we can conclude that the thermal use of groundwater had no considerable influence on the city-wide groundwater temperature of Munich over the measurement period.

In agreement with Dohr and Gruban (1999), we did not observe a significant influence of the sewers. In general, the sewers should contribute to groundwater warming as buildings discharge 15% - 30% of their supplied thermal energy through the sewer system (Schmid, 2008). Thus, the sewer pipes act as a heat carrier, which dissipates heat into the ground mainly through conduction (Frijns et al., 2013; Stauffer et al., 2014). However, also advective heat inflow into the ground can happen through leakage in the pipes. Since waste heat in the mostly shallow sewers is relatively warmer than the ground in winter, its potentially warming impact will be more observable in late winter or early spring (Cipolla and Maglionico, 2014).

In contrast to thermal uses and the sewer system, the heating grid influences the underground only through conductive heat transfer into the ground (Sami and Maltais, 2000; Çomakli et al., 2004; Stauffer et al., 2014). Leakage is rare and in the case of an event only temporary, due to a constant monitoring. Following the indirect observation of Dohr and Gruban (1999), we were able to identify a small influence of the heating grid. This finding is in line with Benz et al. (2015) and Tissen et al. (2019), however, a differentiation must be made between Munich's modern heating grid and the older steam grid with a higher supply temperature. Thus, we suggest reviewing the influence of the heating grid in the future to gain a clearer view of the underlying dependencies.

Contrary to the suggestions by Dohr (1989, 2011), no particular warming effect from large subsurface buildings, underground stations and metro tunnels could be proven on city scale. In the local surroundings of metro tunnels, the depth profile measurements show 2°C to 3°C higher temperatures compared to up-gradient temperatures. The groundwater temperature anomalies, however, mostly dissipate at distances of more than 10m – an observation that is also anticipated for subsurface building structures. A detailed distribution of groundwater temperatures grouped by distance to metro tunnels is provided as supplementary material (cf. SI: Figure 6.11). Locally, our observations are comparable with the thermal impact of underground parking lots studied by Becker and Epting (2021), where the seasonal evaluation also showed that a warming influence is generally the lowest in spring. The study additionally observed that the thermal impact of freeway tunnels is highly seasonal, i.e. a cooling influence in late winter and spring and a warming influence in late summer and autumn. Therefore, the absence of a city-wide warming influence of subsurface buildings and tunnels can also result from the high dependence on usage and seasonality. Epting et al. (2017b) has highlighted that tracking the diffuse conductive thermal impact of subsurface building structures by down-gradient temperature measurements is challenging. Due to the city-wide investigation, the locally observed influences might be largely overshadowed by the dominant spatial factors; local warming would also be more intense in winter (Dohr, 1989). Lastly the regression analysis could not establish a significant influence by surface waters on the groundwater temperature. In general, a cooling influence from surface waters would be expected as relatively cooler lake water infiltrates into the aquifer during the winter and spring months. This cold plume moves down-gradient through advective heat transport and should still be observable in measurements made from May to June (Anderson, 2005). However, since surface waters with substantial groundwater infiltration are only located on the northern border of the study area, most measurement wells are not influenced by them and, consequently, little influence was anticipated. In addition, it must be noted that the influence of the river Isar was outside the scope of this study, because the river is mostly the receiving water and river water infiltration commonly influences the narrow surroundings of the river bed.

In summary, the comparative analysis provided conclusive information for the selection of dominant predictors. Hence, the following depth-dependent examination could reveal novel insights on the change of influences in the shallow gravel aquifer of Munich. Initially, it can be stated that the driving influences observed do not decline with depth, which supports the approach of SSUHI studies covering influences below the seasonal fluctuation zone (Ferguson and Woodbury, 2004; Reiter, 2007; Menberg et al., 2013a; Benz et al., 2018; Hemmerle et al., 2019). However, the influences of hydrogeological factors show greater variability with depth. In part, this behaviour can be attributed to the different heat transport mechanisms described above. For the Darcy velocity, the results indicate that the magnitude of dispersive mixing is most relevant near the surface. At shallow depths, higher temperature gradients are present, which dissipate faster than lower gradients. Therefore, the Darcy velocity becomes less relevant in deeper sections of the aquifer, i.e., below 10 mbgl, where higher temperature gradients are no longer present.

In the depth-dependent analyses of saturated thickness and depth-to-water, however, spatial implications must also be considered. The deeper groundwater temperatures are measured, the larger the possible depth-to-water and the higher the chance that the measurement will be made in a lower section of the aquifer. An increasing depth-to-water steadily increases the insulating effect and thus, the influence also grows continuously. A similar dependency can be observed for saturated thickness. With greater depth, the volume of water that needs to be heated increases, and at the same time the greater volume offers space for horizontal advective heat transport. Consequently, the possible cooling effect of saturated thickness also increases.

Finally, an appropriate basis for the spatial evaluation of thermal influences on an urban aquifer is introduced by the thermal exposure mapping (see Figure 6.9). The results explain the origin of specific temperature patterns in the groundwater and reveal a strong interaction with the surface. As a shown in Figure 6.1e, we observe a compartmentalised SSUHI below Munich similar to the description of the UHI (Funk et al., 2014). Large parks like the *Englischer Garten* and the *Nymphenburger Schlosspark* are responsible for a substantial cooling of the groundwater (cf. Figure 6.1e and Figure 6.9). However, the cooling influence of intermediate sized parks is also evident near the city centre (cf. SI: Figure 6.10). In addition, it must be noted that the groundwater temperatures in April 2014 still reflected different seasonal conditions, because they were measured 1 m below groundwater level. As it is visible in Figure 6.1d, the depths-to-water in the northern, north-eastern and north-western parts of the city are lower than in the south. Therefore, these shallower measurements have a tendency towards lower temperatures, especially in April when the seasonal temperatures at depths from 2 mbgl to 6 mbgl are among the lowest of the year (see Figure 6.3a). Despite this characteristic, a reasonably strong correlation between the exposure score and the interpolated groundwater temperature provides further verification of the significance of the dependencies derived throughout the entire study area.

6.5 Conclusions

Urban environmental authorities nowadays implement sophisticated strategies to reduce greenhouse gas emissions and to protect valuable natural resources. Urban groundwater bodies in particular are subject to warming, which can threaten groundwater quality. However, for groundwater, the development of policies is not straightforward, since there is a conflict between the priorities of thermal use and groundwater protection. It is therefore crucial to understand the dependency and importance of each influential factor before city-wide groundwater protection strategies can be drafted. With this paper, we offer a resilient and comprehensive assessment of the anthropogenic and natural factors that have a significant influence on the groundwater temperature in the shallow aquifer of Munich. A database of temperature time series, depth profiles and a variety of high-resolution spatial datasets allowed the statistical analysis of a depth-dependent change in influence among the dominant factors.

Based on our results, we suggest that often neglected hydrogeological factors should be considered in studies on the SSUHI effect, since they play a key role as mitigating factors. Furthermore, the adjustment of multi-temporal measurements within the zone of seasonal fluctuation delivered appropriate results and is applicable to similar shallow urban aquifers if time series data is available. Finally, the influences identified deliver valuable information on the parametrisation and definition of boundary conditions in numerical models. Above all, the surface temperature boundary condition in shallow aquifers has a key influence on the simulation of thermal anomalies.

Concerning future groundwater monitoring networks, it becomes visible how important it is to capture the temporal dynamic and a vertical resolution. In addition, a monitoring network should be spatially balanced. Since measurements are often carried out to observe the impact of specific point sources, the interpretation on a city-scale can be biased. The outcome that thermal uses and specific underground structures, like sewers, tunnels and deep basements, cannot establish a city-wide significant influence, whereas sealing and built-up areas that have a strong influence on groundwater warming can help to establish measures for mitigating elevated urban groundwater temperatures. Hence, the debate about preserving the thermal conditions of the groundwater should focus more on dealing with large-scale factors and integrating this aspect into urban planning. For instance, the Sponge City Concept could help mitigate groundwater warming in cities (Zevenbergen et al., 2018).

6.6 Acknowledgements

The financial support for this research within the Geo.KW project by the Federal Ministry for Economic Affairs and Energy (BMWi) under Grant Number 03ETW004A is gratefully acknowledged. Further, we thank Patrick Kotyla, Teresa Zölch (Referat für Klima und Umweltschutz), Immanuel Pache (Stadtwerke München) and Tobias Leichtle (Deutsches Zentrum für Luft- und Raumfahrt) for their valuable and essential support with data and additional information.

6.7 Supplementary Information

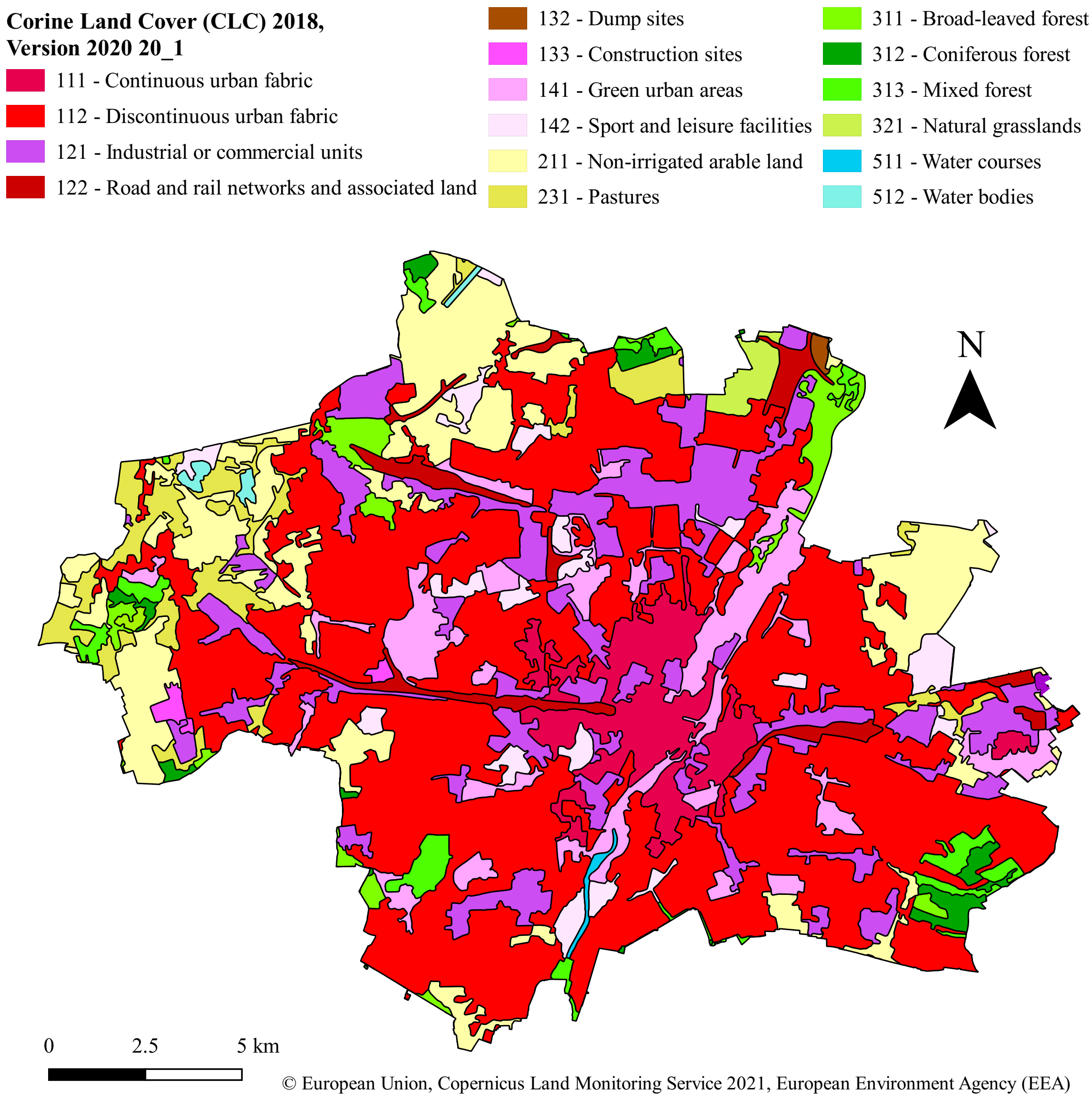


Figure 6.10: Corine Land Cover (CLC) dataset produced within the frame the Copernicus Land Monitoring Service referring to the land cover and land use status of the year 2018.

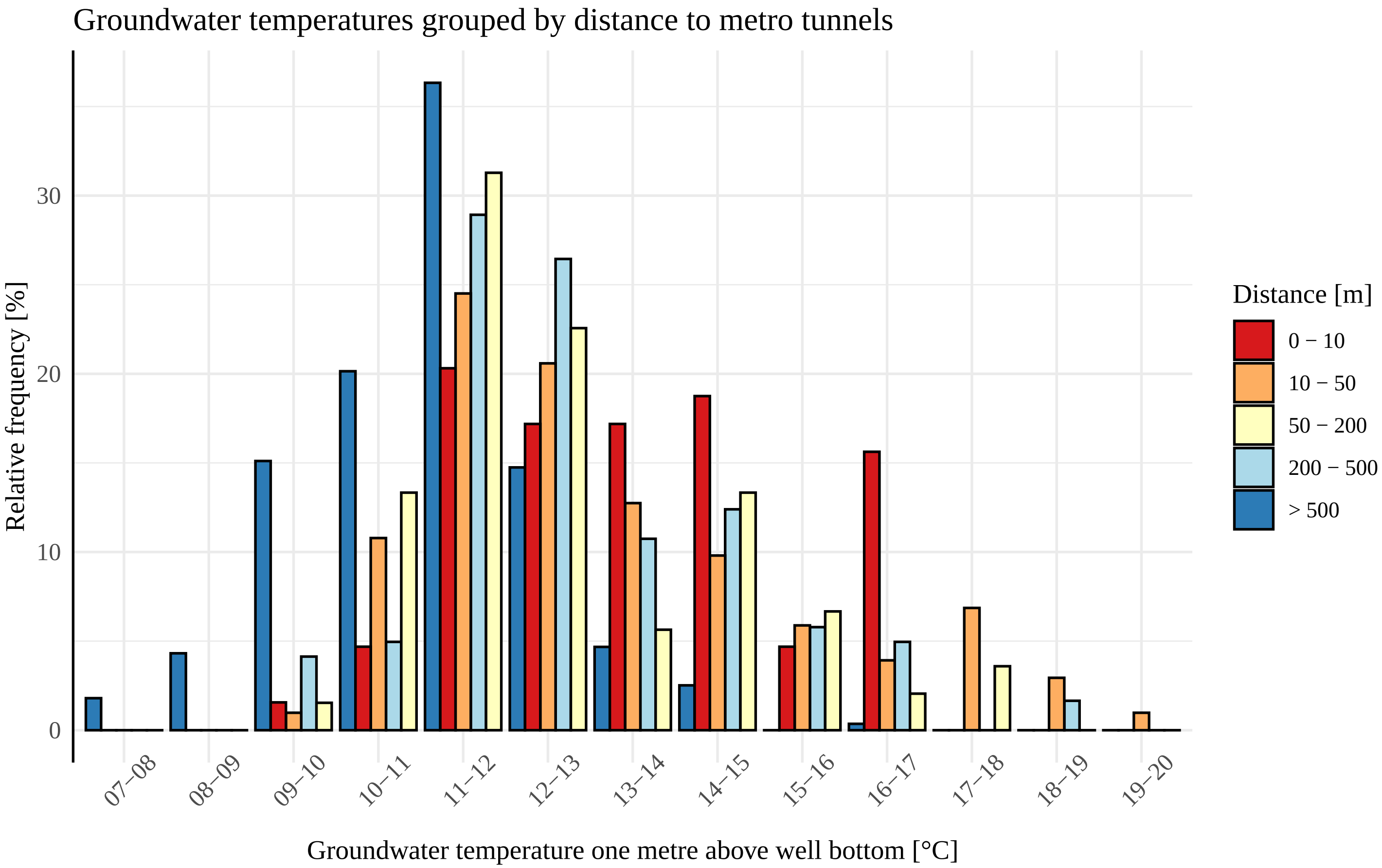


Figure 6.11: Groundwater temperature distribution at April 2014 grouped by distance to metro tunnels.

Chapter 7

Main findings and synoptic discussion

The upcoming sections revisit themes explored in Böttcher et al. (2019), Epting et al. (2020) and Böttcher and Zosseder (2021), which are presented in Chapters 4, 5 and 6, respectively. This chapter will further expand and restructure the main findings and developments to draw a comprehensive conclusion and to emphasize the connections between the different studies. The subsequent sections will demonstrate that only by combining hydraulic and thermal assessment strategies the potential of thermal groundwater use in urban environments can be captured comprehensively.

7.1 How can we apply technical potentials of thermal groundwater use in energy planning?

The TAP-method, introduced in Chapter 4, provides a quantitative approach for assessing the potential for thermal groundwater use. It incorporates three regulatory and operational constraints to ensure sustainable operation of well doublets. These include:

- Limiting the extraction flow rate to avoid a drawdown exceeding one-third of the undisturbed saturated aquifer thickness.
- Ensuring that the injection flow rate does not lead to a groundwater level rise of more than $0.5m$ beneath the ground surface.
- Setting the well doublet's flow rate to a level where hydraulic breakthrough is avoided.

The functional relationships needed to compute the previously mentioned flow rate constraints were determined through non-linear regression analyses. The data required for estimating the regression coefficients was derived from numerous numerical simulations carried out in a parameter study with idealized box-models, as discussed in Section 4.2.2. Unlike the analytical methods used in prior studies, the numerical approach also takes into account the mutual effect of wells on each other, as outlined in Section 2.1. Simulating the entire well doublets resulted in 18% higher extraction rates and 10% higher injection rates when compared to a single-well analysis, i.e., the simulation of extraction only or injection only. The flexibility of the numerical approach also facilitated further investigation into the hydraulic footprint of well doublets for spatial analyses. This was accomplished by simulating multiple well doublets placed successively closer to each other perpendicular to the groundwater flow direction, as illustrated in Section 4.2.4. By quantifying the proportion of recycled water volume with increasingly closer well doublets, a threshold for the sustainable operation of well galleries with multiple extraction and injection wells was established (see Figure 4.3). Consequently, the TAP-method not only provides estimates of the maximum technical potential of well doublets but also offers initial evaluations of larger thermal uses that require multiple extraction and injection wells, such as for low-temperature local heating networks. The results provide crucial input for energy planning in the heating & cooling sector of municipalities. Moreover, the assessment process can be adapted based on the datasets available, thereby offering flexibility and applicability across different scales and contexts.

Typically, the parameters necessary for the TAP-method can be derived from three fundamental datasets, as depicted in Figure 7.1. At the very least, groundwater contours must be available, preferably interpolated from a dense collection of reference date measurements. Continuous data on the water table can be used to directly calculate the groundwater flow direction and the hydraulic gradient. When combined with a commonly available high-resolution digital elevation model, the depth to water can be determined through simple subtraction. The greatest source of uncertainty usually stems from spatial information on hydraulic conductivity and aquifer confinement to the bottom, i.e., the aquifer base. A robust 3-D geological model of the aquifer base requires an extensive dataset of carefully reviewed and classified lithological borehole logs, which is only available in regions with advanced hydrogeological mapping (Albarrán-Ordás and Zosseder, 2020; Theel et al., 2020). As such, conservative assumptions about the aquifer base are often necessary. A similar issue arises for datasets on hydraulic conductivity. Since conductivities are preferably derived from aquifer tests, which are time-consuming and require substantial workforce and preparation, they are typically not available in large quantities. Consequently, conductivity ranges are often derived from literature values that are available for the geologic layers present in the specific study area. In the following, the

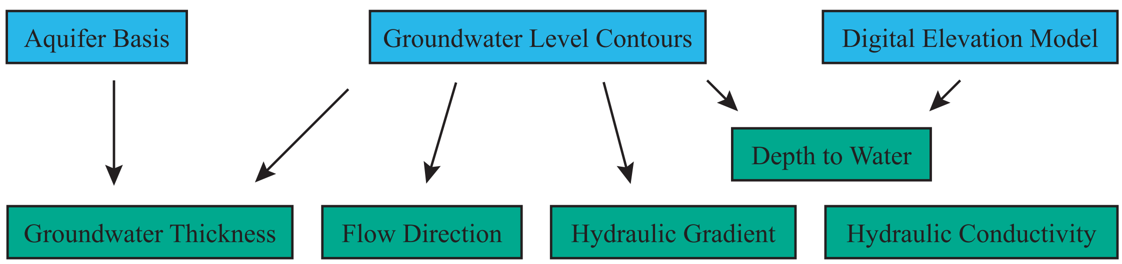


Figure 7.1: Required hydrogeological datasets for a complete calculation of technical potential in the TAP-method (green boxes) for the use in energy planning with the usually available basic datasets to derive them (blue boxes).

two approaches of potential assessment, i.e., the raster-based and the plot-based evaluation as shown in Figure 4.6, will be introduced with examples.

The raster-based assessment using the TAP-method was applied across six case study areas in the Alpine region as part of the GRETA project (2016 - 2019). These areas, along with their respective evaluations, are presented in Figure 7.2. The cases include Munich and Basel, as introduced in Chapters 4 and 5, as well as smaller regions like the Upper Illertal in Bavaria (Germany), Leogang in the Salzburger Land (Austria), Parc de Bauges in Savoie (France), and Aosta in the Aosta Valley (Italy). For each case, the geothermal power of the source, denoted P_{geo}, is calculated from the standard temperature difference (ΔT) in the source heat exchanger of a water/water heat pump, typically $5K$. The calculation also involves the volumetric heat capacity of water (C_w) and the technical flow rate ($\dot{V}_{tech}$) of a well doublet set $10m$ apart. The calculation is as follows:

$$P_{geo} = \dot{V}_{tech} \cdot C_\mathrm{w} \cdot \Delta T \tag{7.1}$$

Hence, by estimating a coefficient of performance (COP), the resulting heating or cooling power output of the heat pump (P_{hp}) can be derived using the following equation:

$$P_{hp} = P_{geo} \cdot \frac{COP}{COP - 1} \tag{7.2}$$

The methodology demonstrated in Figure 7.2 relies on georeferenced raster datasets of the hydrogeological properties outlined in Figure 7.1. As explained in Section 4.3.2, this raster-based approach does not depend on the available space for drilling or the demand. The well distance is set to a constant value, thereby emphasizing the influence of the hydrogeological parameters. Consequently, this approach is particularly effective for comparing different locations and identifying the most suitable regions for new installations.

All four case studies are situated in Alpine valleys filled with Pleistocene and Holocene deposits primarily composed of glacio-fluvial materials and, to a lesser extent, glacio-lacustrine sediments. Consequently, it could be expected that areas dominated by gravel would hold high potential for thermal groundwater use. However, the need for a detailed potential analysis was also evident to discern the influence of areas dominated by silt or clay, such as lake deposits.

In the Upper Iller valley, this applies to the less suitable northern areas, as indicated by the red color in Figure 7.2a. In this region, the narrowing of the valley caused the Iller river to form a lake during the Pleistocene period, where fine-grained sediments now confine the thin overlaying Holocene gravel aquifer at the bottom (Scholz, 2016). Moreover, the deeply excavated U-shaped valley, carved out by glacial erosion, holds high potential areas in the southern basin structures (Reusch, 2017). On the valley sides, a rapid decline in saturated aquifer thickness from thinner sediments leads to a reduced potential, a pattern also evident in the assessment results (Hornung, 2017).

Similar geological processes shaped the narrow valley of Leogang. The results depicted in Figure 7.2b demonstrate how the thin aquifer in the west significantly reduces the available potential. On the contrary, in the east, the wider valley exit leading towards Saalfelden am Steinernen Meer features a deep gravel filling and high hydraulic conductivities, contributing to high potential values.

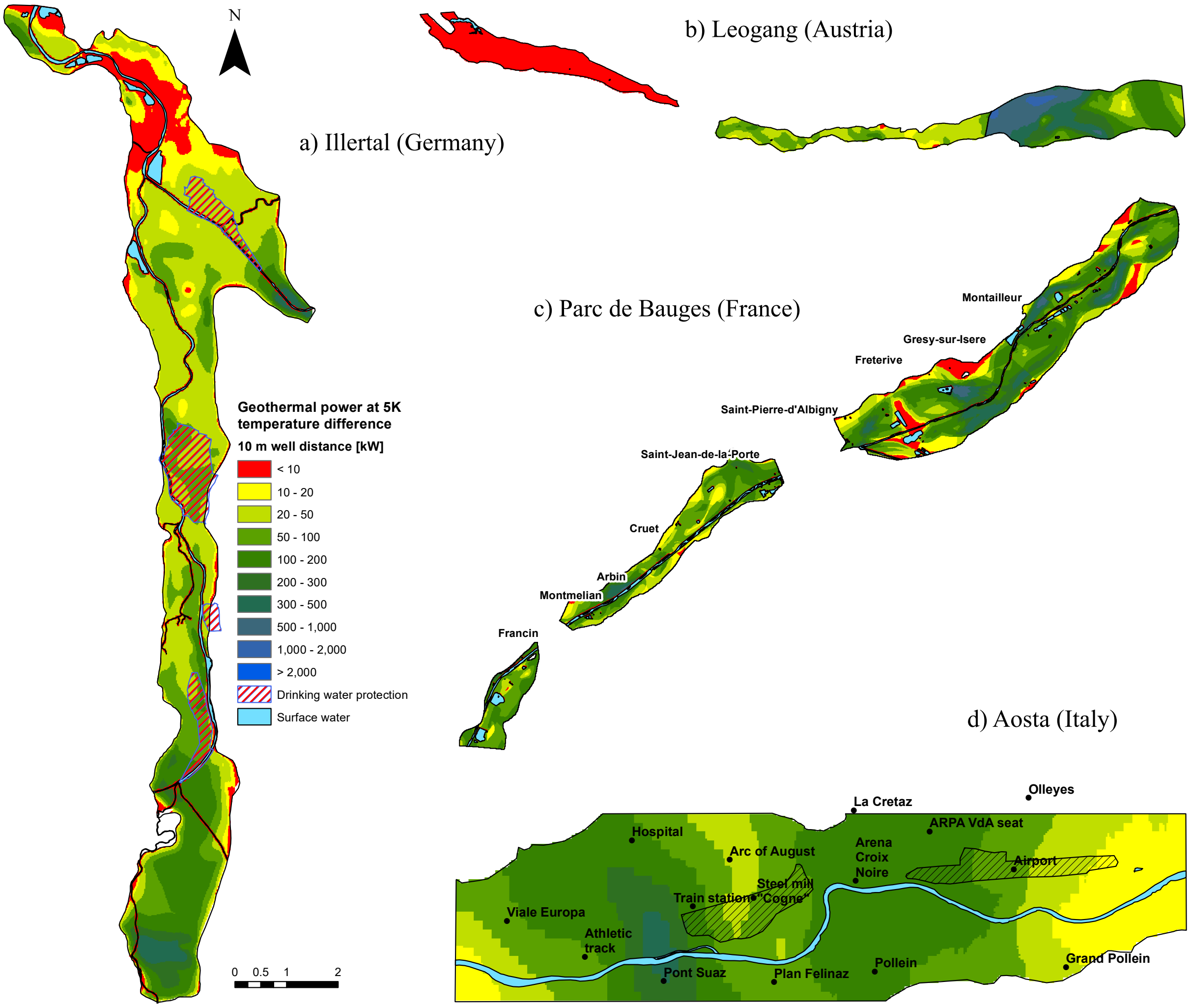


Figure 7.2: Power of the geothermal source (groundwater) at a $5K$ temperature difference and a well distance of $10m$ derived from the technical flow rate of the TAP-method for the four case study areas of the GRETA project a) Upper Iller valley, b) Leogang, c) Parc de Bauges and d) Aosta through equation 7.1.

In the case of the assessment for Parc de Bauges, an additional characteristic of the study site limits the potential. Adjacent to the river, the depth to water is extremely low, falling below the $0.5m$ safety threshold used in equation 4.4 to define the injection well flow rate. Consequently, the central red values depicted in Figure 7.2c mark areas with no injection potential. Towards the valley sides, similar to the Iller valley, a reduced saturated thickness also diminishes the potential for thermal use of groundwater.

Finally, in the region surrounding the city of Aosta, there are no constraints except the hydraulic breakthrough, as defined by equation 4.2. Consequently, the region features an adequately thick and deep aquifer, resulting in the drawdown and level rise due to extraction and injection not reaching the defined thresholds before a hydraulic breakthrough occurs in well doublets distanced at $10m$. This leads to moderate and high potentials that are primarily determined by a variation in hydraulic conductivity, as seen in Figure 7.2d.

As demonstrated by the interpretation of the results, the raster-based assessment approach is particularly useful for evaluating different regions within a case study area. In addition to calculating technical potentials from a representative well doublet with a fixed distance, it enables the identification of governing hydrogeological parameters. Hence, also the influence of a parameter's spatial variation on the resulting potential becomes visible.

However, specific local characteristics, such as the availability of drilling sites or a maximum well distance dependent on site-specific space, are absent in the raster-based approach. To address these limitations, a second assessment approach based on the specific plot of land has been developed. This method is particularly suitable for application in spatial energy planning and will be introduced in the following sections.

The plot-based approach for energy planning involves three main steps:

1. **Review of the Current Heating & Cooling Supply and Demand:** This step involves gathering data on the existing energy infrastructure, including heating or cooling grid, gas network, and distributed systems like oil, liquefied gas, or heat pumps. Since detailed information about the heating and cooling demand of individual buildings may not be readily available, it is often necessary to use simulation methods to estimate these demands on a building level.

2. **Assessment of the Potential of Suitable Heating & Cooling Technologies:** This step focuses on assessing the quantitative potential of preferably renewable heating and cooling technologies. This is where techniques like the TAP-method could be instrumental in determining the potential for geothermal energy use.

3. **Matching of the Available Potential with the Demand:** In this final step, the potential of each technology is matched with the demand to analyse its possible contribution to

future heating and cooling supply scenarios. This contributes to an understanding which technologies can meet the energy demand effectively and sustainably.

Through these steps, the plot-based approach aims to provide a comprehensive assessment of the current and potential energy scenario in a region, and subsequently facilitates the development of future sustainable energy plans.

The procedures for potential assessment are tailored to the specific characteristics of the respective technology. From technologies already commonly considered in energy planning, we can derive key aspects that are also relevant for integrating thermal groundwater use in a variety of ways. Therefore, we examine the procedures employed for solar thermal energy as a distributed system and subsequently heat from biogas plants as a more centralised solution. In the case of rooftop-installed solar thermal systems, estimating the energy potential on the roof surface area per building provides the most precise analysis to capture the spatial potential (Thebault et al., 2020; Groppi et al., 2018). The suitable rooftop area is constrained by superstructures such as chimneys, dormers, and rooftop windows, while the possible thermal energy output of a panel is governed by factors like solar irradiation, roof azimuth, and inclination (Gassar and Cha, 2021). These governing factors are unique to each roof, and they can be compared with the hydrogeological parameters on a plot of land needed to estimate the potential for thermal groundwater use. Just as each roof's characteristics determine the potential for solar energy, each plot's hydrogeological parameters can determine the potential for thermal groundwater use.

The initial step in a plot-wise potential assessment involves aggregating the required five parameters for each plot of land (see Figure 7.1). An appropriate aggregation procedure is the calculation of median values rather than mean values, as extreme values are less impactful in the median (Witte and Witte, 2017). Hydrogeological datasets typically exhibit only slight variations on a plot-of-land scale in urban environments, given that such plots are usually quite small. For larger plots, however, the assumption of constant and isotropic values across the entire plot may lead to significant bias and should be carefully reviewed within the specific study area.

In the case of thermal groundwater use, defining suitable drilling space for new wells on a plot of land is comparable to evaluating the available rooftop area for solar thermal systems. Just as roof superstructures limit solar panel installation, buildings on a plot restrict where drilling can occur. Even smaller mobile rigs are typically too tall to fit into underground garages. Additionally, mandatory minimum distances from borders and buildings must be maintained on each plot, further defining the availability of drilling sites. For the actual extraction and injection locations on a plot, the wells are positioned at the furthest points upstream and downstream within the suitable drilling area, as demonstrated in Figure 7.3a. The derived maximum distance between wells often constrains the potential in hydrogeologically suitable areas (see Section 4.3.2 and Figure 4.6b). Once the maximum well distance is determined, a plot-based evaluation of the technical potential can be conducted. This result can then be matched with the heating and cooling demand of the buildings on the respective plot. As such, all necessary steps for a comprehensive integration of thermal groundwater use as a distributed system in future energy plans are undertaken. Within the GRETA-project, a plot-based potential assessment was performed for the area of Sonthofen in the Upper Iller valley and for Munich's energy plan in the heating sector.

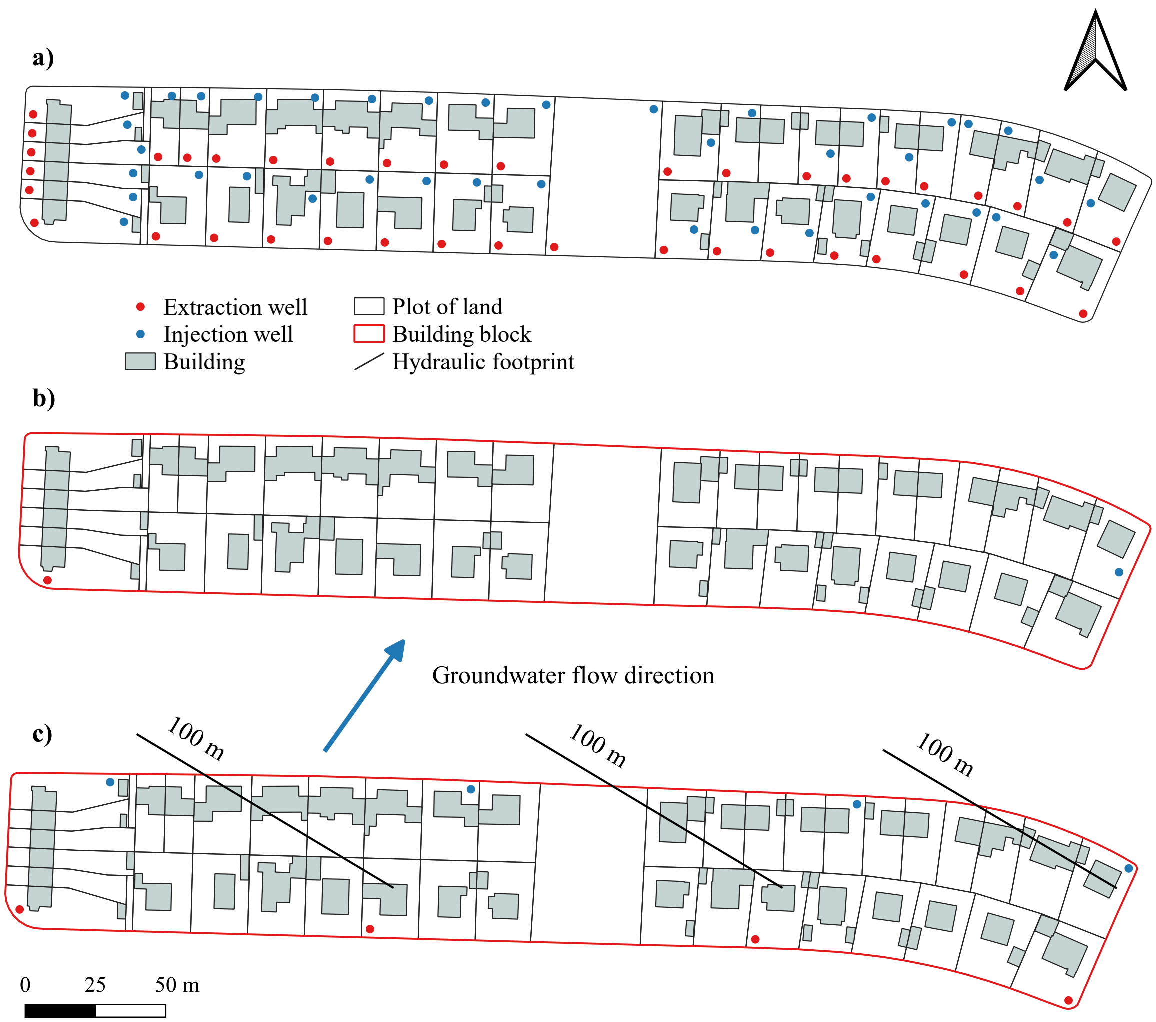


Figure 7.3: a) Exemplary well layout for a plot-based (one well doublet per plot), b) block-based (one well doublet with 400m distance) and c) block-optimised (four well doublets with 50m distance) potential assessment with every well doublet furthest apart from each other and minimum distances of 3m to buildings and plot borders.

Contrary to distributed systems, a biogas plant is a single unit that can supply multiple buildings and requires a costly heat distribution system, i.e., a local heating grid. The cost-efficiency of a newly installed grid typically increases in neighbourhoods with a higher spatial density of demand. For the evaluation of suitable local or large heating grid layouts, mature methods are already available for use in spatial energy planning (Dochev et al., 2018; Steingrube et al., 2021; Jiang et al., 2022). Consequently, these methods can be applied in a similar fashion to larger-scale thermal groundwater uses, as only the source changes. A biomass plant can be replaced by a well system enhanced with an industrial-grade heat pump to supply the grid. Another configuration is distributing groundwater from a central well system to heat pumps located directly at each user, in what's known as a low-temperature local heating grid (see Section 1.2).

In the case of local heating grids where an entire settlement is supplied, the available space for well installations increases, as multiple plots of land are available for drilling. Additionally, local heating grids are usually planned by public energy suppliers, who are permitted to drill on public ground, such as in streets or parks. Consequently, the area of interest for the spatial analysis of drilling sites shifts from individual plots to building blocks or districts, as demonstrated in Figure 7.3b, where the maximum well distance is approximately 400m. With the potential for increased well distances, the hydraulic breakthrough constraint of the TAP-method might no longer be the limitation for the technical flow rate. As the well distances become larger, the drawdown or injection constraint could eventually become the limiting

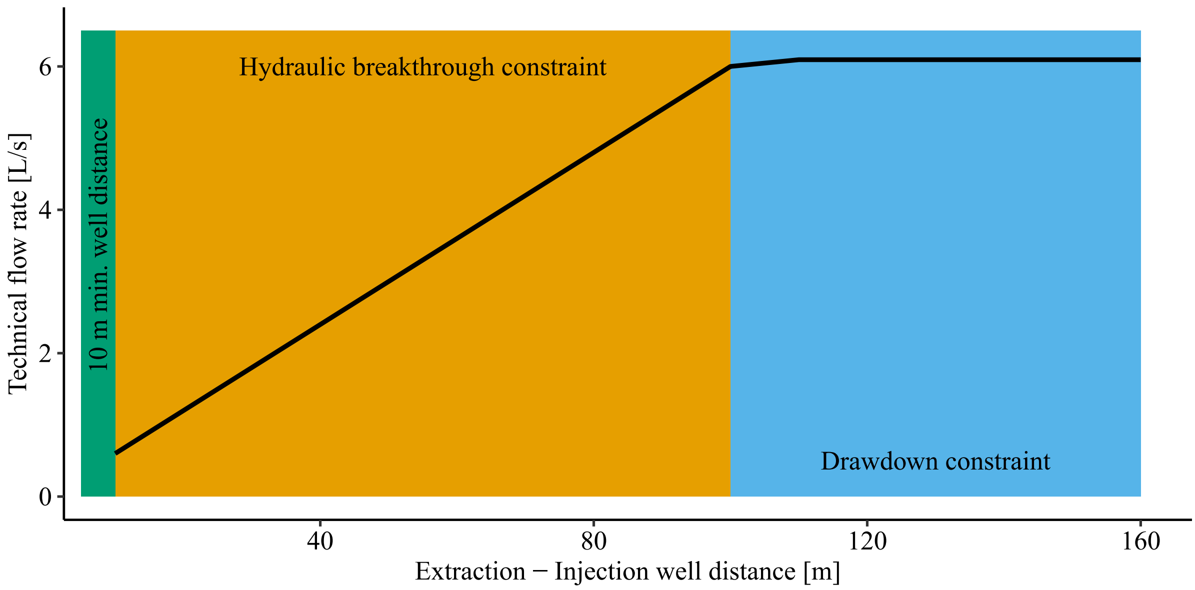


Figure 7.4: Exemplary technical flow rate development for increasing well distances to visualize a change of the hydraulic breakthrough to the drawdown constraint after a distance of more than 100m with typical hydrogeological parameters, i.e. $k_f = 5 * 10^{-3} m/s$; $b = 2.5m$; $g = 3‰$, in the quaternary aquifer of Munich (cf. equation 4.1 and 4.2).

factor (see Figure 7.4). Equation 4.3 was derived to calculate the well distance at which the hydraulic breakthrough alternates with the drawdown as the constraining factor. In the case shown in Figure 7.4 for an exemplary hydrogeological setting, this point is reached at a distance of around $100m$. Assuming that the hydraulically influenced area of a well doublet can be defined as twice the width of the well distance, the hydraulic footprint of the exemplary system is a square with around $200m$ edge length (see Figure 4.3). Consequently, well distances of more than $100m$ will not lead to higher technical flow rates, but to larger hydraulic footprints. Therefore, a well doublet, as in the example shown in Figure 7.3b, with a distance of $400m$ is unnecessarily far apart, which drives up costs for piping and is not space-efficient.

If more space than the already occupied square with $200m$ edge length is available, the extractable energy can be further increased by installing additional well doublets in so-called galleries. These should be situated next to each other and perpendicular to the natural groundwater flow direction. This approach is illustrated in Figure 7.3c, where four well doublets, each approximately $50m$ apart, are installed with a perpendicular distance of $100m$ from each other. Therefore, the required four squares with $100m$ edge length can be placed on the building block, and the available water for thermal use in the entire system is doubled compared to the layout with one doublet, as shown in Figure 7.3b. Assuming the extraction values given in Figure 7.4, the block-based well layout yields $6L/s$ and the block-optimized four system layout yields $12L/s$ (see Figure 7.3b-c). In summary, the TAP-method can be adapted with different spatial approaches to the specific scale or task in the potential assessment, even for the supply of local grids.

Particularly with an application in larger regions, several limitations of the TAP-method need to be considered. Since a comprehensive summary is already provided in Section 4.4, this section will focus solely on energy planning related limitations. The most significant characteristic of the method is that it only carries out a maximised assessment in the area of interest, i.e., one plot or one block, without considering neighbouring areas. If the potentials are used for consulting homeowners interested in switching their heating system, the maximum potential per plot is exactly the desired information. However, if spatially aggregated results are required to assess the potential of an entire district or city, the presented procedures are not applicable. This is clearly evident in Figure 7.3a, where the injection wells of upstream plots are often located right next to the extraction well of downstream plots. Consequently, the thermal anomaly of the upstream system would negatively influence the downstream system, decreasing its performance. For an assessment of spatial potentials, the method would need to incorporate the areas of resulting thermal anomalies.

Given that the TAP-method is entirely based on hydraulic numerical simulations, it's essential to account for a bias towards increasingly conservative results for larger well distances and seasonal loads. The potential available may be underestimated depending on the temporal characteristics of the demand, due to the assumption of steady-state flow conditions. In general, the effect of energy storage in the solid phase will delay the propagation of a thermal anomaly. The temperature front lags the fluid front in relation to the ratio of rock/water volumetric heat capacities, which is known as thermal retardation (Shook, 2001; Gossler et al., 2019). Thus, the hydraulic breakthrough that is considered in the TAP-method occurs earlier than the thermal breakthrough. This time difference can be neglected for relatively constant loads, since a steady temperature field will eventually develop, validating the upfront assumption of steady-state. The same is true for small well distances, as quasi steady-state thermal conditions are quickly established, and the results serve as operational peak loads rather than temporally aggregated values like monthly averages.

However, when a load curve peaks over a relatively short period of time, both flow and heat transport are highly dynamic. For a maximised and sustainable operation, one would operate a well doublet at pumping rates where the thermal anomaly reaches the extraction well exactly at the time when the operation phase ends or is phasing out. Subsequently, the depression and infiltration cone gradually disappear and the thermal anomaly dissipates downstream as the natural gradient resumes control over the flow field. As a result, the next operation period can start from pristine conditions.

This maximised case can not occur when the hydraulic recycling of water is prohibited, as the thermal anomaly won't be pulled towards extraction since no water from the injection is entering the extraction. Therefore, the shorter the operational period of the planned thermal use, the greater the potential underestimation by the hydraulic breakthrough constraint. For larger well distances, the same holds true, since the propagation of the thermal front from injection to extraction might already take the usual heating period of around 5 months (Halilovic et al., 2021). Consequently, the recycling of water could also be admitted without the occurrence of a thermal breakthrough. In conclusion, the tendency towards more conservative estimations is an advantage of the method. However, for edge cases on specific sites, these characteristics need to be understood in order to decide whether a system is feasible or not.

7.2 Which factors govern the thermal state of shallow urban aquifers?

The temperature level of an aquifer defines its energy content. Depending on the type of usage, the temperature can significantly affect the available potential for thermal use of groundwater. For cooling purposes, in Bavaria, it is only permitted to inject water with a maximum temperature of 20°C. However, large areas within the City of Munich are not suitable for cooling usage because the groundwater temperature is already anthropogenically warmed and close to the limit of 20°C (see Figure 6.9). The mapping of such areas is just one example of how a detailed understanding of an aquifer's thermal regime is necessary to contribute to a comprehensive potential evaluation of thermal groundwater use in urban environments.

As presented in Chapter 6, an extensive statistical analysis of the SSUHI effect was conducted, which comparatively evaluates four natural and nine anthropogenic influences in the shallow aquifer of Munich. Additionally, an approach was developed to statistically adjust the seasonal variation in temperature measurements taken at different times to a single reference date. This adjustment allowed for an unbiased view of the impact strength of thermal influences. Through an additional depth-dependent analysis, vertical changes in impact strength were revealed in detail. Lastly, a thermal exposure score was derived from the prior findings. This score supports a spatial evaluation of the aquifer's vulnerability to elevated temperatures and separates zones where thermal use for heating or cooling is favourable due to local differences in groundwater temperature.

The findings presented in Section 6.3.1 confirm that the seasonal ambient temperature oscillation is the main natural influence on the shallow urban aquifer of Munich. Using a passive heat tracing method, the average thermal diffusivity was estimated, and a typical temperature depth-profile of the studied area was derived. This profile still shows significant seasonal temperature variations up to 10 meters below ground level (*mbgl*) (see Figure 2.3). Previous studies on SSUHI effects, as discussed in Section 2.2, often circumvent the challenge of capturing the different seasonal influences in shallow temperature measurements. These studies either used deeper temperatures below the zone of seasonal fluctuations or considered seasonal influences negligible. In the approach presented here, shallow measurements could also be integrated in a statistically meaningful manner by subtracting different seasonal temperature conditions to study the remaining influences without bias, as presented in Section 6.3.1. However, this was only possible because a high-quality spatial and temporal dataset of temperature depth profiles and multi-annual time series measurements was available in the study area (cf. Section 6.2.2).

Following the seasonal detrending, the correlation and regression analysis of all influential factors revealed that surface sealing and build-up area are the most dominant influences on large-scale anthropogenic heating of the Quaternary aquifer in Munich. Interestingly, a significant warming effect was also observed for the city's heating grid. Additionally, the study underscores the crucial role that hydrogeological conditions play in mitigating elevated groundwater temperatures. Thus, their influence is significant not only in the hydraulic analysis of the potential but also in the thermal analysis. In the regression analysis, the saturated thickness emerged as the dominant reducing factor, followed by the depth to water and the Darcy velocity. The findings underscore the importance of high-quality spatial datasets for capturing the heterogeneity of SSUHI effects. As discussed in Section 2.2, this required level of detail was often missing in previous studies. However, when these findings are qualitatively compared, they are largely consistent with those of other SSUHI studies (cf. Section 6.4.2). A direct comparison between surface sealing and building data indicated that sealing is a superior parameter for describing the anthropogenic influence from changed land use at the surface and should be preferred if available.

The analysis also identified several factors that did not significantly influence the SSUHI in this comparative study of Munich, as discussed in Section 6.4.2. These factors include the sewer system, thermal uses for heating and cooling, deep buildings, tunnels, metro stations, and surface waters. In part, these results can be attributed to specific characteristics of the dataset and the context of the case study. For instance, for the surface waters studied, a direct interaction with the surrounding aquifer is present, and a cooling influence should be observable (Anderson, 2005). However, only a few measurement points were located downstream of surface waters, so no significant influence was detected in the statistical approach at the city-scale. Similarly, the impact of tunnels and metro stations was not significant at the city-scale. Generally, a local warming influence would have been expected and was indeed observed by Dohr (1989). This local influence was further confirmed by a more detailed examination of areas near metro tunnels, where the measured temperature distribution shifts towards warmer temperatures closer to the tunnels, as shown in Figure 6.11.

When it comes to larger sewers, similar characteristics likely apply, although these were not investigated in detail after the initial analysis showed no significant impact on the SSUHI. An improved analysis of thermal interactions should carefully consider the installation depth of the respective sewer pipes, as these are typically not buried in the saturated zone unless the depth to groundwater is quite shallow. Similarly, for deep-grounded buildings, no significant effect on the SSUHI was observed. This finding aligns with those of Epting et al. (2017b) and Becker and Epting (2021), who highlighted the rapid diffusion of thermal impacts at larger distances from the source. Finally, the absence of a significant impact from thermal uses, where resulting thermal anomalies have been widely documented in many studies, can likely be attributed to the timing of the temperature measurements used in this analysis. The measurements were taken from April to June, a period during which the heating season has typically ended and the cooling season has not yet begun in most cases. Therefore, the lack of an observed influence from thermal uses cannot be generalised for the entire year and may change at the end of periods of high demand.

The additional depth-oriented analysis of the five dominant influences showed that the mitigating effect of the hydrogeologic parameters, namely the saturated thickness, depth to water, and Darcy velocity, changes significantly with depth below ground (see Figure 6.8). For saturated thickness, a steep increase in relevance was observed from the surface to $10 mbgl$, with consistently high values for greater depths. Consequently, future studies on aquifers primarily situated more than $10 mbgl$ should consider saturated thickness as a significant factor in the formation of a SSUHI. As for depth to water, a steady increase in importance towards greater depths was observed, reaching values comparable to those of saturated thickness at depths of $18 - 20mbgl$. These values support the hypothesis that an increased thickness of the unsaturated zone acts as an insulator against thermal influences from the surface (cf. Section 6.3.2). Conversely, the importance of Darcy velocity gradually diminishes until it becomes insignificant at depths greater than $10mbgl$. This suggests that Darcy velocity can be omitted when studying SSUHI effects in deeper aquifers. This aligns with the hypothesised behaviour, as higher flow velocities lead to more intense mixing of the groundwater, thereby reducing temperature gradients that are typically steeper in shallower layers. The dominant driving influences on the SSUHI, namely the heating grid and surface sealing, showed less variation with increasing depths. The heating grid consistently contributed to a slight but steady warming, consistent with the expected influence. On the other hand, surface sealing clearly emerged as the main driver of the SSUHI in Munich's aquifer.

The insights gained regarding the influence of various factors were further synthesised through the definition of a score that describes the susceptibility of urban groundwater to anthropogenic warming. This *thermal exposure score* consolidates the driving and mitigating influences of the four dominant spatial factors, indicating on a scale from 1 to -1 how much warming can be anticipated from the urban environment. The effectiveness of this score was confirmed by correlating it with independently measured groundwater temperatures, as illustrated in Figure 6.9.

In conclusion, the statistical approach developed in this study has provided robust results for a comprehensive evaluation of the SSUHI at the city-scale. However, two main limitations of the study design must be highlighted. First, the static evaluation over a relatively narrow time span cannot capture seasonally dynamic processes, such as the operation of thermal uses. Despite this limitation, the results are still valid for the time period analysed, indicating that thermal uses for cooling do not present a year-round issue for warming of the urban aquifer in Munich. Second, the main characteristic of correlation and regression analyses, as used in this statistical approach, is that they always consider the entire population of observations. While this approach is suitable for testing the significance of factors across an entire city area, it can overshadow local phenomena by regionally dominant influences, since every factor is evaluated in comparison with all other factors. Consequently, the study of specific local influences, such as heat dissipation from underground building structures, should not be analysed statistically at a city-scale. Therefore, the results should be interpreted with these limitations in mind, particularly when considering local or temporally dynamic phenomena.

The insights obtained regarding the thermal conditions and influences on Munich's shallow aquifer enable a seasonal and usage-specific potential assessment. By computing a "typical winter season" temperature map, the efficiency of groundwater heat pumps can be estimated, thereby pinpointing thermally attractive locations for installations. Simultaneously, advisories to avoid drilling shallow wells in areas with low water depth can be issued, in cases where groundwater temperature would fall too low in early spring. Conversely, a ”typical summer season” temperature map can help identify areas where cooling applications would be disallowed due to already high temperature levels. These considerations will be incorporated into the new energy strategy of the City of Munich, thus enriching the potential assessment of thermal groundwater use. The seasonal and usage-specific approach to assessing the potential of thermal groundwater use is not just innovative but also reduces planning risks. It ensures that the thermal potential of groundwater is harnessed optimally and sustainably, while minimising potential negative impacts on the groundwater system. Ultimately, this will contribute to Munich’s broader goals for energy efficiency and climate protection.

7.3 Synthesis

This thesis has significantly enabled a more accurate quantitative evaluation of the potential for thermal groundwater use, while also contributing to a more detailed understanding of the thermal influences present in shallow urban groundwater bodies. In the first phase, a novel method has been developed to assess the technical extraction potential for the thermal use of groundwater, integrating operational and regulatory limits. The potential for technical flow rate between extraction and injection wells is estimated via three key hydraulic constraints. These constraints safeguard against excessive drawdown in the extraction well, overflowing of the groundwater table in the injection well, and hydraulic breakthrough in the well doublet. Moreover, the method also accounts for mutual hydraulic interference between well doublets, enabling a calculation of feasible spatial density that does not result in significant water cycling between wells. This potential assessment methodology has been applied to two case studies in the cities of Munich, Germany, and Basel, Switzerland. The results underline the critical importance of each hydraulic constraint, especially in areas with low aquifer thickness or depth to water. Comparing technical flow rate estimates with actual monthly groundwater extractions from large open-loop systems demonstrates the efficacy of the results as reliable and conservative peak extraction estimates. Importantly, the TAP-method provides quantitative potential values grounded on a highly adaptable and transferable numerical approach. This paves the way for more accurate planning and sustainable utilization of thermal groundwater resources in urban environments.

The application of the TAP-method in Basel further demonstrated its flexibility in a comparative evaluation with passive energy extraction systems at different spatial scales for an integrated energy planning procedure. The potentials for thermal groundwater use were derived through a combination of the TAP-Method and high-resolution 3D groundwater flow and heat-transport models. The technical potential for both ’active’ (open-loop groundwater use by well doublets) and 'passive' (energy absorbers) use was thoroughly assessed. The focus was on a systematic evaluation of different parameters to estimate energy potentials across both the entire urban area of Basel and within 18 selected city quarters. This included the analysis of advective energy transport with groundwater flow, and differentiating between thermal energy stored in the fluid phase, the solid phase, and their combined total. The potential energy derived from absorber systems installed in subsurface building envelopes was also considered. In each city quarter, technically feasible flow rates were calculated, which facilitated the derivation of different energy potentials. These specially developed potential measures are then employed to offer a comparative analysis of the energy potential, enabling a preliminary suitability assessment. By providing a comprehensive, multi-scalar, and comparative evaluation of both 'active' and 'passive' extraction systems, this study opens up new possibilities for urban energy planning and sustainable resource use.

To ensure the success of energy plans and strategies, the safeguarding of groundwater as a drinking water resource is paramount, especially considering the expected increase in thermal groundwater use. This means that the competing priorities of thermal use and groundwater protection have to be balanced in future energy plans, a task which is far from straightforward. A deep understanding of the thermal condition of shallow aquifers is thus essential to any assessment of their potential for thermal use. This is particularly true for urban groundwater bodies, which often undergo warming. While this warming can increase the efficiency of groundwater heat pumps, it also poses potential threats to groundwater quality. Understanding the relationships and importance of each influencing factor is a vital prerequisite for developing city-wide groundwater protection strategies. This thesis contributes significantly to this understanding by offering a comprehensive examination of the anthropogenic and natural factors influencing the temperature of the shallow aquifer in Munich. A large database of temperature time series, depth profiles, and a variety of high-resolution spatial datasets was utilised to conduct a statistical analysis identifying dominant factors and demonstrating changes of their influence with depth. This approach allowed important insights into the dynamics of the SSUHI effect, as well as to develop a score that captures the vulnerability of urban groundwater to anthropogenic warming.

The results of this thesis underline the crucial role that often overlooked hydrogeological factors play in mitigating the effects of the SSUHI. Therefore, these factors should be incorporated into studies concerning SSUHI effects to ensure accurate results and models. The methodology developed in this thesis to adjust multi-temporal measurements within the zone of seasonal fluctuation has proven successful and can be applied to similar studies in other urban areas with shallow aquifers, assuming that time series data is accessible. An application of the method in Vienna, Austria is currently ongoing. Furthermore, the identified influential factors provide vital insights for numerical modelling, especially in terms of parameterisation and boundary condition definition. It has been shown that the incorporation of surface temperature oscillation through a boundary condition at the model's top layer has a profound impact on the simulation of thermal anomalies in shallow aquifers. If this factor is neglected, the cooling effect from increased thermal exchange with the surface will not be simulated, leading to overestimations of the extent of thermal anomalies compared to real-world conditions.

When it comes to future groundwater monitoring networks, the importance of capturing temporal dynamics and maintaining a vertical resolution becomes evident. Additionally, such networks should be spatially balanced. Measurements are often taken to observe the impact of specific point sources, which can bias interpretations on a city-wide scale. The results show that thermal uses and specific underground structures, such as sewers, tunnels, and deep basements, cannot exert a city-wide significant influence. On the other hand, a precise knowledge about the factors surface sealing and built-up areas, which have a strong influence on groundwater warming, can aid in establishing measures to mitigate elevated urban groundwater temperatures. Therefore, the discussion about preserving the groundwater's thermal conditions should shift more towards addressing these large-scale factors and integrating these considerations into urban planning, such as the concept of sponge cities and the preservation of permeable ground.

In conclusion, the methods developed are well-suited to serve as a tool for integrating thermal groundwater potentials into future energy strategies, not only in Munich and Basel, but in similar environments globally. Architects, city planners, and potential users can gain initial site-specific information on the technical feasibility of sustainable geothermal energy use in the context of urban development and construction projects. Additionally, the results of these assessments can support spatial planning and be integrated into urban energy plans, fostering the use of renewable energy and reducing fossil fuel consumption.

Chapter 8

Future developments and outlook

As addressed in the Sections 4.4, 5.4 and 6.4, some features, such as the consideration of thermal anomalies, are still missing in the presented research and in the following links to related topics are introduced to further improve a comprehensive thermal groundwater management in urban environments. This chapter will start with an overview of future potential assessments with the TAP-method and continue with an outline of several paths for future developments that would close the identified gaps of the current approach.

Recently, the TAP-method was integrated in a Bavaria-wide potential assessment of shallow geothermal energy comprising the three main extraction systems, i.e. borehole heat exchangers, ground heat collectors and groundwater wells. All three systems were evaluated quantitatively on a raster-based and plot-based level, as presented for the thermal use of groundwater in the Sections 4.3.2 and 7.1. Within the project, also a publication of the results on the federal geodata service platforms *Bayerischer Energieatlas* and *Bayerischer Umweltatlas* was conducted (Staatsregierung, 2022; LfU, 2022). The approval of the project and the publication also showed the positive evaluation of the TAP-method by the Bavarian authorities and was a great success in the large-scale application of the method.

Furthermore, the TAP-potential in the City of Munich already became a fixed component in the newly established urban energy planning, which is the follow-up of the already mentioned energy plan of the heating sector (cf. Section 7.1). The integration within the practical work level of city's authorities can be considered the second important success in the application of the method. The ensured ongoing improvement of the practical use will eventually serve as a best-practice example for other municipalities and cities. Within the urban energy planning concept, the plot-wise assessment is used to update highly accurate building heating & cooling demands from the local energy supplier for the decision support in a multi-agent model (Bousquet and Le Page, 2004). Hence, the potentials can be used to derive long-term strategies under certain scenarios, e.g. change of incentives, change of refurbishment rates or energy prices. On a local urban scale, the assessment results are further used to supply information for integrated concepts in city quarters. In such cases, an initial feasibility evaluation of specific solutions, like distributed or central supply, is commonly needed. Here the TAP-method can also be combined with an estimation of seasonal groundwater temperatures to include the system's efficiency in economic calculations. The estimations are possible through the detailed knowledge on Munich's SSUHI and the passive heat tracing as presented in Section 6.3. In detail, equation 6.1 can be used to calculate the seasonal temperature fluctuation time and depth dependent. Hence, with an initial planning of the extraction well depth, a temporal variation of the mixed temperature of the water pumped can be estimated similar to the values shown in Figure 2.3. For a resilient estimation of the mixed pumping temperature, however, a more precise knowledge about the thermal influences within the water column of a well would be needed. Since depth of the well screen, vertical variations in geology and the existing temperature gradient play a significant site-specific influence, an in-depth analysis of how to estimate mixed pumping temperatures would be necessary.

The largest room for improvement in the TAP-method is the integration of heat transport. While the conservative nature of including the hydraulic breakthrough as constraining element is suitable for the assessment of smaller systems or continuos loads, an accurate assessment of larger systems needs to consider thermal processes, as well. This accounts for an estimation of the thermal feedback within one system, but also for an estimation of the resulting thermal anomaly downstream of the injection well that might negatively influence other existing systems. As the latter is considered to be the most crucial task in a spatial potential evaluation of thermal groundwater use, it is discussed more in detail in the following Section.

8.1 The next step: An optimized spatial potential for thermal groundwater use

The next improvement of the TAP-method involves enhancing the resulting technical potentials with spatial considerations that allow the assessment of an entire aquifer or urban district. Besides the already integrated hydraulic footprint, as explained in Sections 4.2.4 and 7.1, a thermal footprint also needs to be considered. In the example of a densely populated neighbourhood, it becomes clear that not every building can implement a groundwater heat pump. This is because the cold temperature anomaly that disperses downstream from an injection well will eventually interfere with extraction wells of downstream systems. Since the tolerated thermal interference is commonly set to a limit of $1K$ temperature change at the downstream well, the area consumed by the thermal anomaly above a $1K$ change can be defined as the thermal footprint of a system. Figure 8.1 visualises an exemplary well layout within a neighbourhood of 56 plots where 44 plots are able to supply their heating demand with a groundwater heat pump without violating the $1K$ temperature change constraint at extraction wells.

In porous media, such as productive gravel aquifers, the lateral extent of thermal anomalies can be estimated using analytical equations (Pophillat et al., 2020), or more sophisticatedly, by using numerical simulations of flow and heat transport (Bundschuh and Suarez, 2010). However, even with these solutions at hand for delineating thermal anomalies, the specific positioning of wells is not straightforward. Consequently, the question arises as to how well doublets can be arranged to maximise the spatial potential. Such a question can only be properly answered through an optimisation process that ideally identifies a globally optimal solution within the domain. Especially when considering already existing thermal uses and different types of usage, such as heating or cooling, manual allocation of wells is simply not feasible and will probably not lead to a global optimum.

During the Geo.KW project (2019 - 2021), I teamed up with colleagues to tackle different optimisation challenges (Halilovic et al., 2023a). Initially, we developed a new method for determining the optimal layout of groundwater heat pump wells using the adjoint approach, which efficiently solves a Partial Differential Equation (PDE)-constrained optimiszation problem (Halilovic et al., 2021). In this approach, the Finite Element Method (FEM) is employed to numerically solve the forward model that describes flow and heat transport in the aquifer. The optimisation algorithm "moves" the wells in the plots of land, within the feasible drilling areas. These areas are defined with respect to the boundaries and buildings, as shown in Figure 4.6b. However, a significant drawback of the numerically coupled optimisation is the high computational cost, which increases drastically with more complex and larger areas of interest.

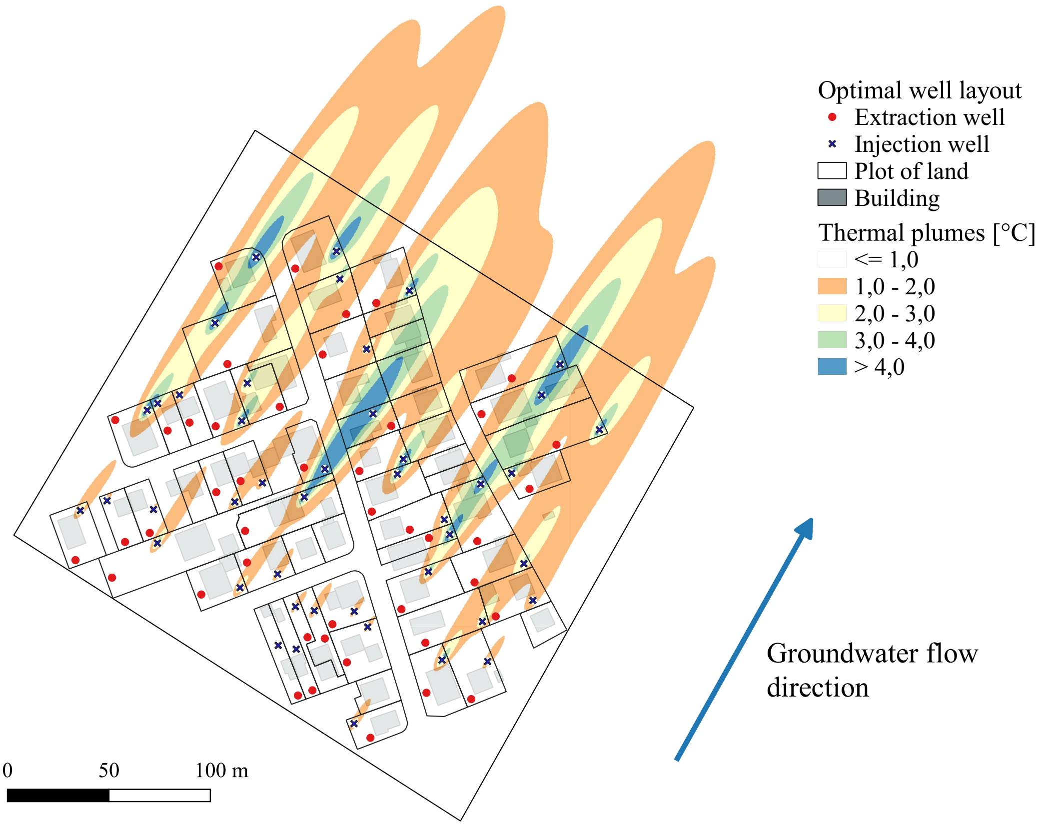


Figure 8.1: Optimal well locations to maximise the spatial potential of an exemplary neighbourhood with the constraint of less than $1K$ temperature change from upstream thermal plumes at downstream extraction wells (modified after Halilovic et al. (2023b)).

As a result, its application to entire city districts encompassing thousands of plots is currently not feasible.

One way to significantly reduce computational cost is the substitution of the FEM model with a simpler analytical model. Additionally, the optimisation problem can be simplified by transforming it into an integer linear programming problem. This can be achieved by reducing the degrees of freedom for possible well locations. As a result, the free movement of wells must be replaced by a selection process among a finite number of discrete well positions. In response to these considerations, a second optimisation approach was developed by Halilovic et al. (2023b). This approach uses the analytical solution of the Linear Advective Heat Model (LAHM) to compute the temperature field. The LAHM equation, originally developed by Kinzelbach (1987), was enhanced with spatial and temporal superposition. This enhancement allows for the calculation of multiple operating injection wells in a transient manner. Optimal well placement is achieved through a selection from predefined well locations. The overall optimisation problem becomes an integer linear program that can be efficiently solved even in larger districts with numerous well doublets (Halilovic et al., 2023b). Figure 8.1 provides an example of an optimal well layout derived from the LAHM optimisation approach.

Moving from a spatially maximised optimum, the next logical step in development is integrating the available potential into a city's entire energy system. It's important to acknowledge that it's not always feasible to fully exploit the spatially available potential for thermal groundwater use. To find the most economic or the least carbon dioxide-emissive scenario for a city's heating and cooling supply, all other renewable options must also be considered. For example, a heating grid supplied by a deep geothermal plant generates fewer CO_2-emissions than a groundwater heat pump operating with the current electricity mix in Germany. In areas with large depths to water, the increased costs for drilling and well installation may make air-source heat pumps a more economical solution. As cooling demands rise in the future, the very efficient combined heating and cooling supply with groundwater will need to be taken into account, especially for office buildings and the commercial sector. It's crucial to consider existing energy distribution systems, such as heating grids or future potentially hydrogen-run gas networks, as they have an impact on an optimal heating and cooling supply. The most comprehensive way to include all these factors is to couple a subsurface heat-transport simulation with an energy infrastructure optimisation.

This was the main objective of the Geo.KW project, which aimed to find the most economical and the most CO_2-efficient integration of thermal groundwater use for an entire city (Zosseder et al., 2020). A large-scale 3D-groundwater model, calibrated on the current conditions of the shallow aquifer, accounts for all driving and reducing influences of the urban heat island. It is capable of simulating the temporal dynamics of different heat sources and sinks, including future scenarios that account for the current rate of global warming due to climate change.

Coupled with an energy system optimiser, future scenarios also consider an increased cooling demand during summer. The dynamic groundwater temperatures at potential sites of thermal uses can directly be used as heat pump inlet temperatures, which govern the overall efficiency of the heat pump. Therefore, synergies from upstream to downstream systems are accounted for if heating and cooling uses are appropriately located. However, such comprehensive approaches to analyse the optimal heating and cooling supply of an entire city require massive computational power that can only be supplied by high-performance computing grids.

Consequently, each optimisation approach has its unique field of application and can provide solutions to specific questions. Furthermore, they can be combined to incrementally refine potential evaluations at the specific scale of interest. With an array of different methods now available, the time has come to put them into practice and establish them in best-practice examples for applied energy planning in urban environments.

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